LES of Flow Past Cylinders and Airfoils

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Discovery through simulation

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Outline

- Introduction
- Filtered NS Equations and SGS Model
- Wall-resolved large-eddy simulations (LES)
  - *LES of flow past a cylinder*
    - *Smooth*
    - *Grooved*
    - *Rotating*
- Wall modeled LES
  - *Virtual wall boundary conditions*
- WMLES of flow past airfoils
- Conclusion

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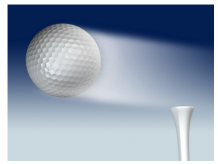
Fluid Mechanics: Reynolds number (*Re*)



Re: 10^3 10^4 10^5 10^6 10^7 10^8 10^9

DNS (Direct Numerical Simulation)

No Modeling

LES (Large-eddy simulation)

Wall-resolved LES

Wall modeled LES

Hybrid RANS-LES

RANS (Reynolds-averaged Navier-Stokes)

Modeling

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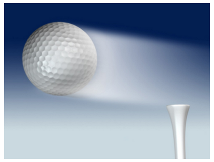
Fluid Mechanics: Reynolds number (*Re*)



Re: 10^3 10^4 10^5 10^6 10^7 10^8 10^9

DNS

Wall-resolved LES

Wall modeled LES or Hybrid RANS-LES

RANS

- *Computer Resources*

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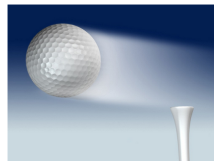
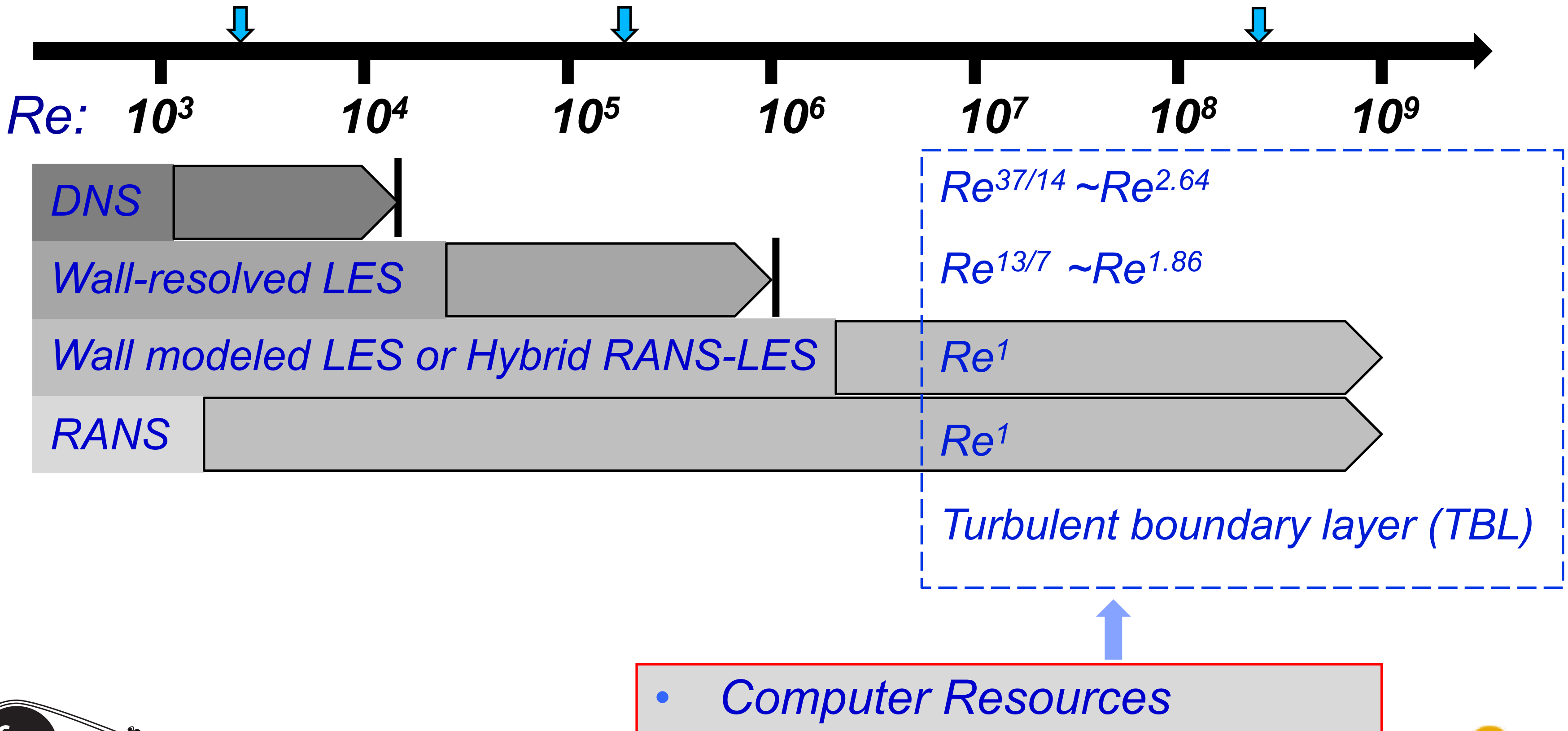
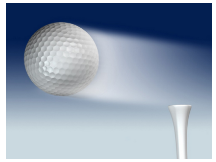
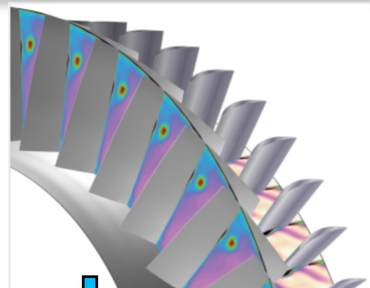
Fluid Mechanics: Reynolds number (*Re*)





Fluid Mechanics: Reynolds number (*Re*)





Re: 10^3 10^4 10^5 10^6 10^7 10^8 10^9

Wall-resolved LES — $Re^{13/7}$ ~$Re^{1.86}$

Wall modeled LES or Hybrid RANS-LES — Re^{1}

Turbulent boundary layer (TBL)

Key flow features:

- *Turbulence*
- *Transition*
- *Separation*

- *Computer Resources*
- *Accurate Modeling/Simulation*

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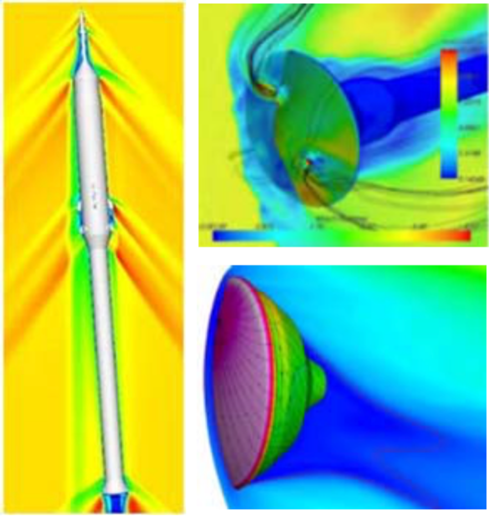
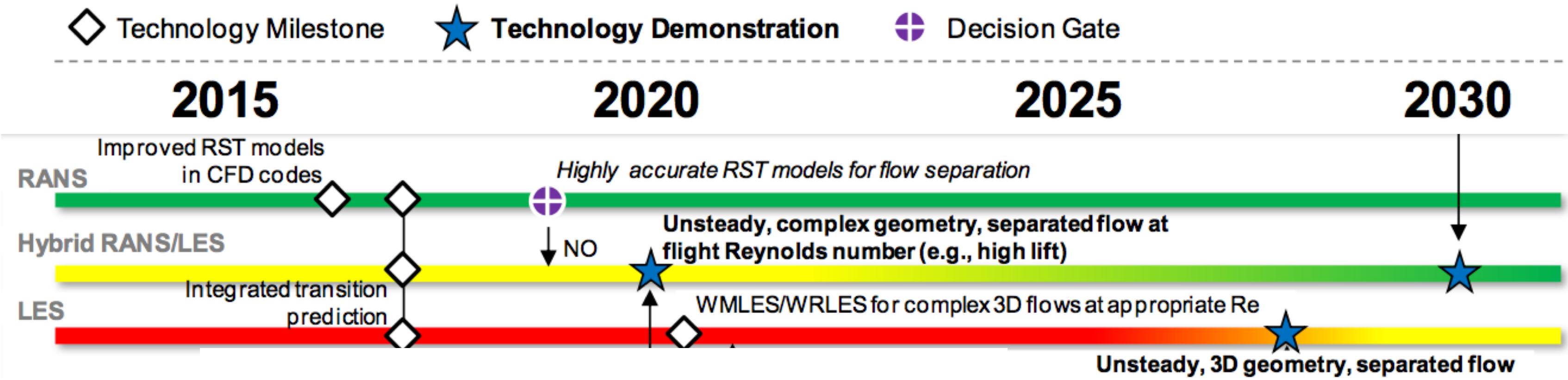
NASA: Critical challenges in CFD ---- Separation

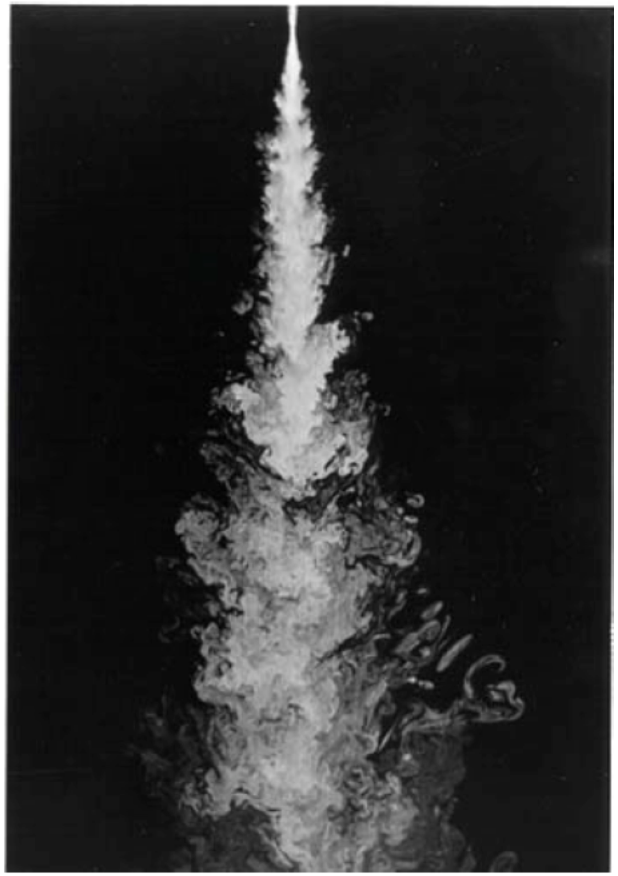
- NASA's 2014 Aerosciences: Top three challenges
  - Prediction of unsteady separated flows
  - Aero-plume interaction prediction
  - Aerothermal prediction



- NASA CFD 2030 VISION



Direct Numerical Simulation (DNS)
Large-Eddy Simulation (LES)



Re = 10k (Dimotakis et al. 1983)

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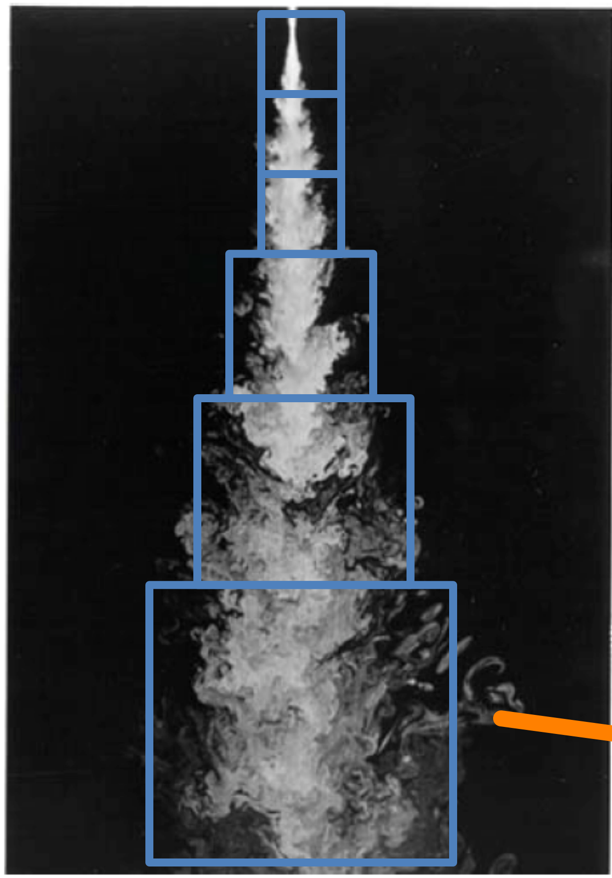
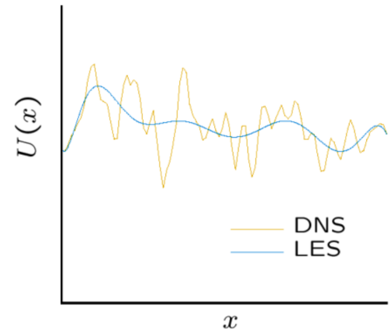
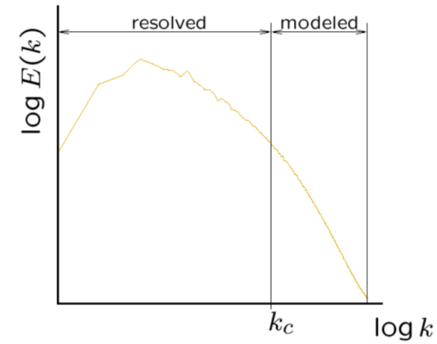
Direct Numerical Simulation (DNS)
Large-Eddy Simulation (LES)



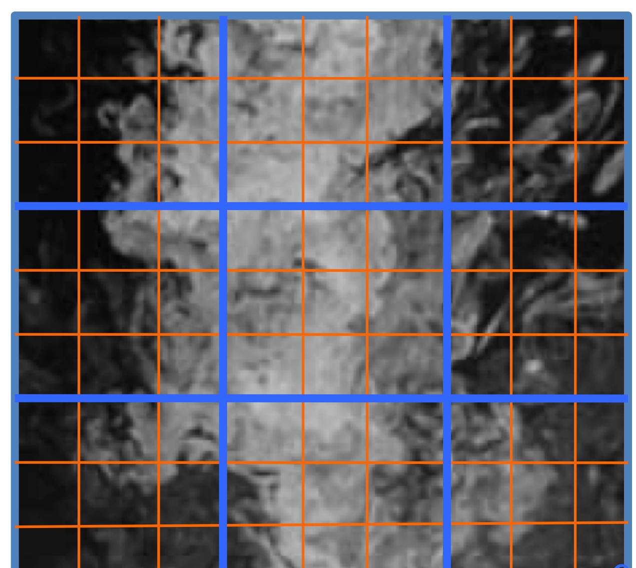
Re = 10k (Dimotakis et al. 1983)



physical space: fine-scale fluctuations not resolved, their influence is modeled.



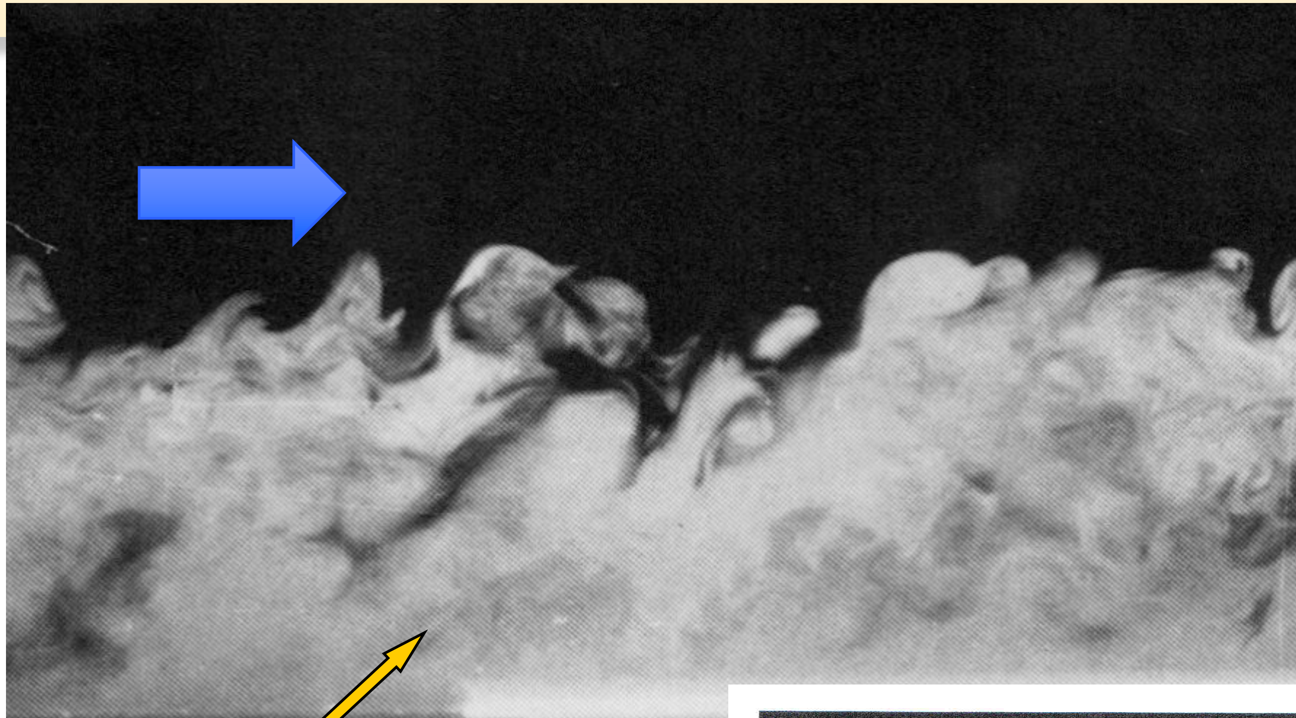
spectral space: resolved range, $k < k_c$ (cutoff wavenumber k_c), subgrid range $k > k_c$.



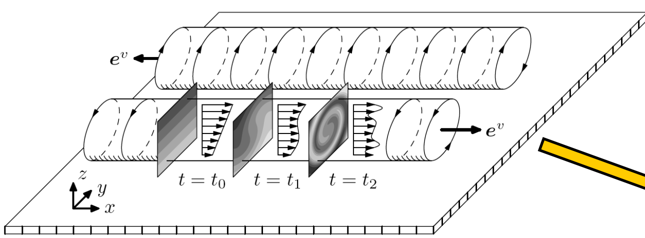
DNS

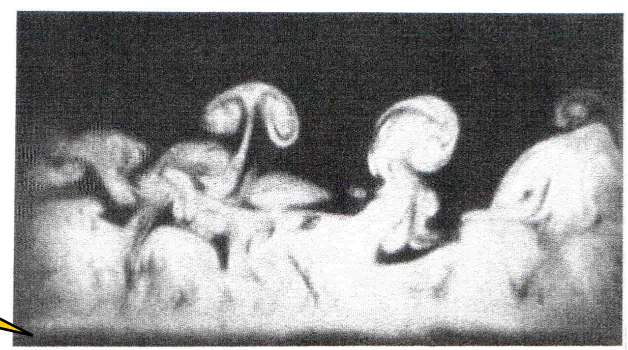
LES

LES for wall-bounded flows



(Falco 1977)





Head & Bandyopandhyay (1981)

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Filtered Navier-Stokes Equations

- Apply filtering operation to incompressible Navier-Stokes equations

$$
\begin{aligned}
\frac{\partial \widetilde{u}_i}{\partial x_i} &= 0 \\
\frac{\partial \widetilde{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\widetilde{u_i u_j}\right) &= -\frac{\partial \widetilde{p}}{\partial x_i} + \nu \frac{\partial^2 \widetilde{u}_i}{\partial x_i^2} \\
\frac{\partial \widetilde{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\widetilde{u}_i \widetilde{u}_j\right) &= -\frac{\partial \widetilde{p}}{\partial x_i} - \frac{\partial}{\partial x_i}\underbrace{\left(\widetilde{u_i u_j} - \widetilde{u}_i \widetilde{u}_j\right)}_{T_{ij}} + \nu \frac{\partial^2 \widetilde{u}_i}{\partial x_i^2} \\
\widetilde{u_i u_j}(\boldsymbol{x}, t) &\equiv \int_{-\infty}^{\infty} \mathcal{G}(\boldsymbol{x}' - \boldsymbol{x})\, u_i(\boldsymbol{x}')\, u_j(\boldsymbol{x}')\, d\boldsymbol{x}' \neq \widetilde{u}_i \widetilde{u}_j
\end{aligned}
$$

- T_{ij} ``unresolved stresses'' must be modeled: this is the ``closure problem''
- This equation set is NOT closed
- Filtering process on NS equations is strictly formal: no particular filter is actually needed

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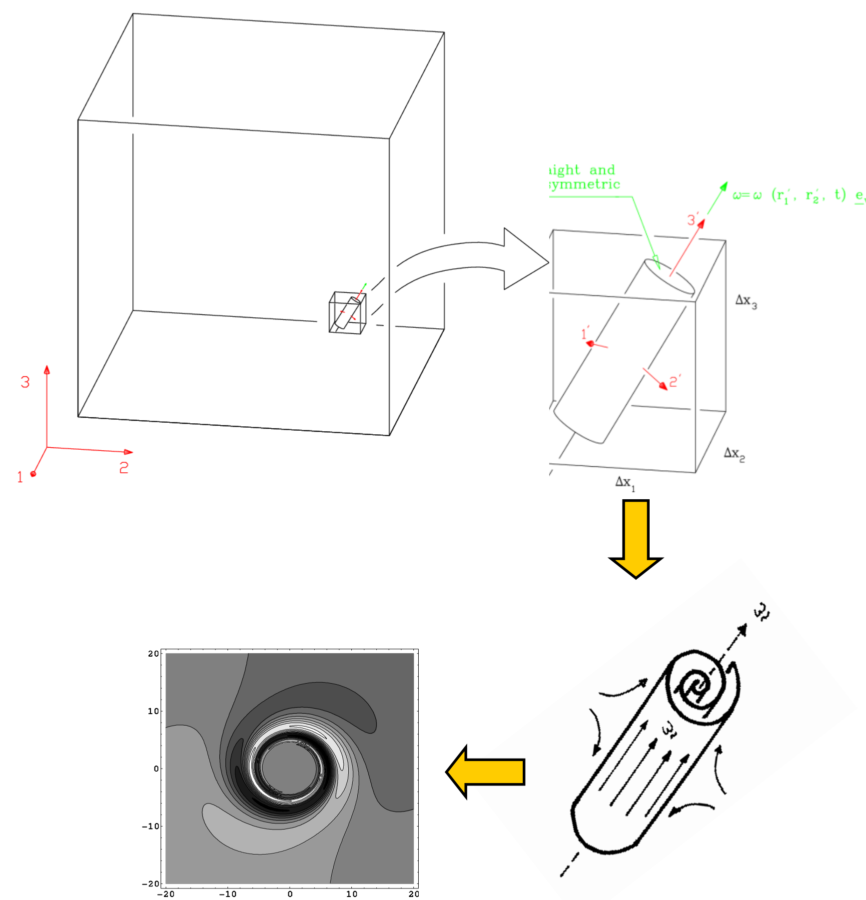
Explicit SGS model: stretched-vortex model

- Structure-based approach
- Subgrid motion represented by nearly axisymmetric vortex tube within each cell
- Local solution of NS equations for stretched-spiral vortex
  - *Lundgren (1982), Pullin & Lundgren (2001)*
- Subgrid stress:

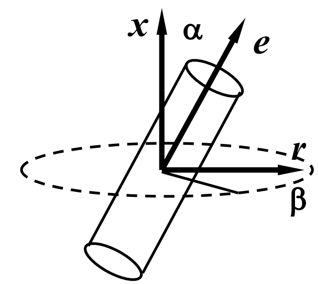


$$\boxed{T_{ij} = (\delta_{ij} - e_i^v e_j^v) K,}$$

$$K = \int_{k_c}^{\infty} E(k)dk = \frac{1}{2}\mathcal{K}_0' \Gamma\left[-1/3, \kappa_c^2\right], \mathcal{K}_0' = \mathcal{K}_0 \epsilon^{2/3} \lambda_v^{2/3}$$

Model parameters

- Subgrid energy spectrum (Lundgren, 1982)



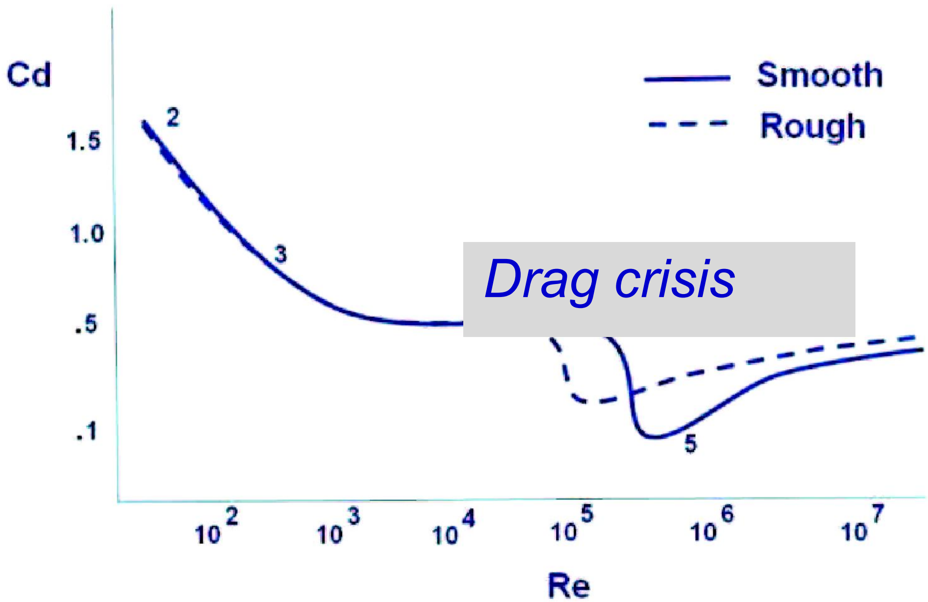
$$
\begin{aligned}
E(k) &= \mathcal{K}_0 \epsilon^{2/3} k^{-5/3} \exp[-2k^2 \nu / (3|\tilde{a}|)] \\
\tilde{a} &= \tilde{S}_{ij} e_i^v e_j^v, \qquad \tilde{S}_{ij} = \frac{1}{2}\left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i}\right)
\end{aligned}
$$

- Parameters obtained from resolved-scale, second order velocity structure-functions (Lesieur et al)

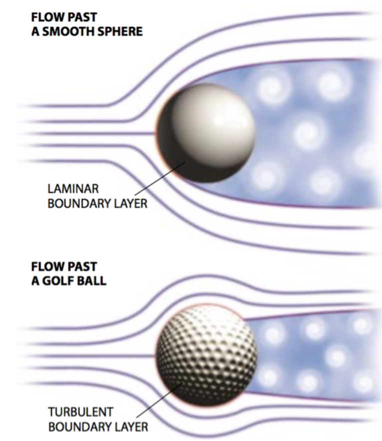
$$
\begin{aligned}
\mathcal{K}_0 \epsilon^{2/3} &= \frac{\overline{\mathcal{F}_2}(\triangle)}{\triangle^{2/3} \mathrm{A}}, \qquad \mathrm{A} = 4 \int_0^{\pi} s^{-5/3} (1 - s^{-1} \sin s) ds \approx 1.90695 \\
\overline{\mathcal{F}_2}(\triangle) &= \frac{1}{6} \sum_{j=1}^{3} \left(\delta \tilde{u}_1^{+\,2} + \delta \tilde{u}_2^{+\,2} + \delta \tilde{u}_3^{+\,2} + \delta \tilde{u}_1^{-\,2} + \delta \tilde{u}_2^{-\,2} + \delta \tilde{u}_3^{-\,2} \right)_j ,
\end{aligned}
$$

- Align SGS vortex axis with principal extensional eigenvector of $\tilde{S}_{ij}$
- See Misra & Pullin (1997), Voelkl & Pullin (2000) for details

Motivation: Drag Crisis



Drag crisis



"Tackling turbulence using Supercomputers" –Kim & Moin 1997

Golf ball trajectory

(https://www.golf-simulators.com/physics.htm)

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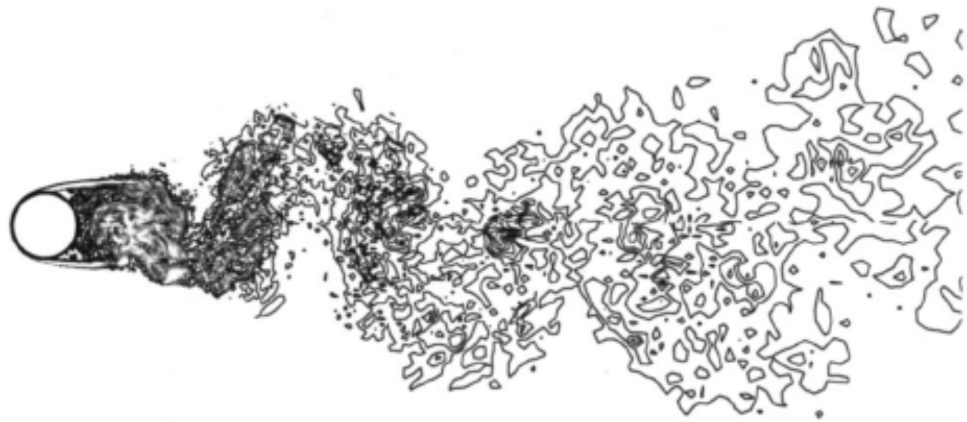
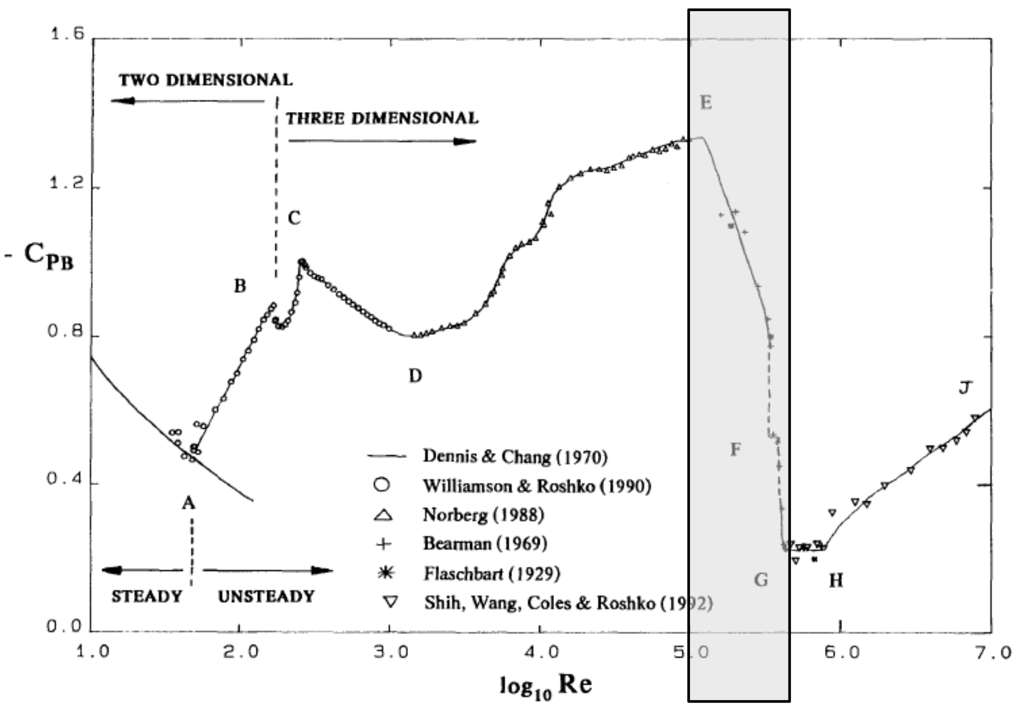
Flow past a cylinder

- SC: Smooth Cylinder
- GC: Grooved Cylinder
- RC: Rotating Cylinder

SC: Background of Flow past a cylinder



Kravchenko & Moin, PoF, 2000



Roshko, JWEIA, 1993

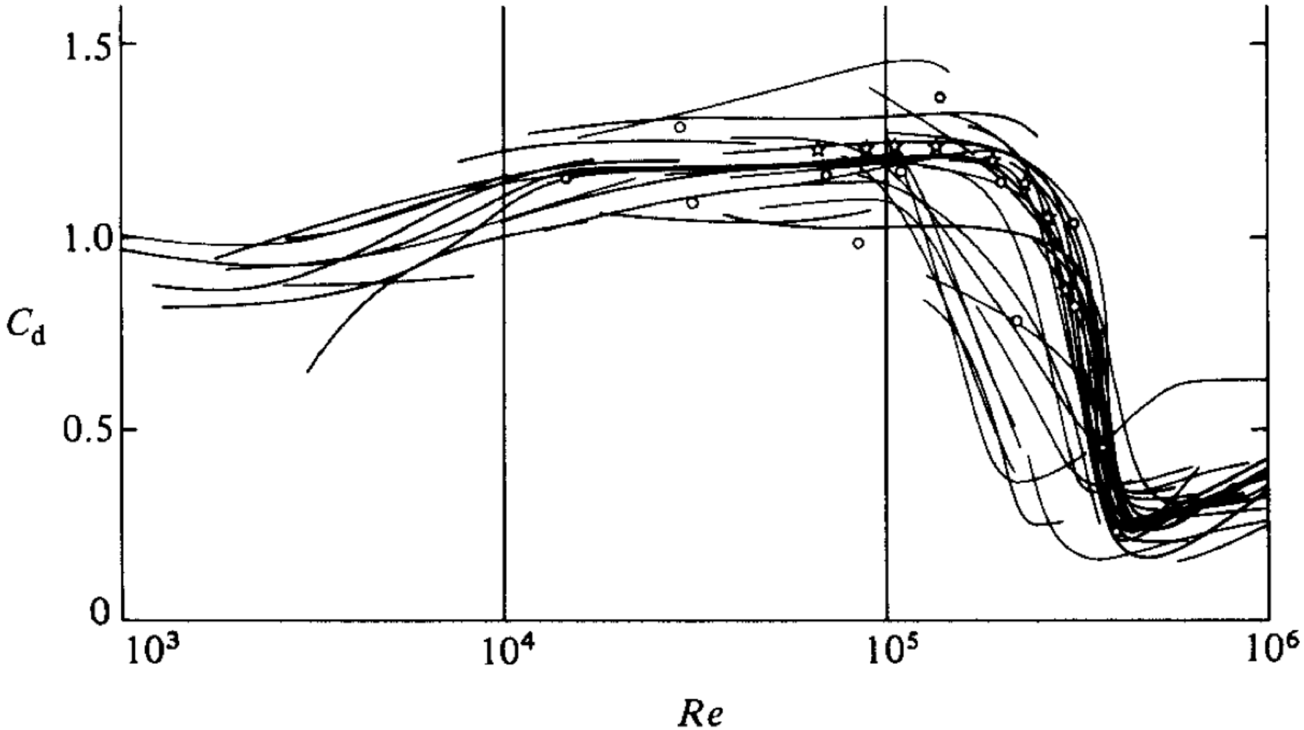
Drag crisis

Conventional explanation

- *Turbulence location*
  - *Wake in subcritical*
  - *BL for supercritical*
- *Any other explanation?*

SC: Drag Coefficient

- Drag coefficient results from experiments do not agree with each other
- Figure from Cantwell & Coles (1983,JFM): exp. Data from literature



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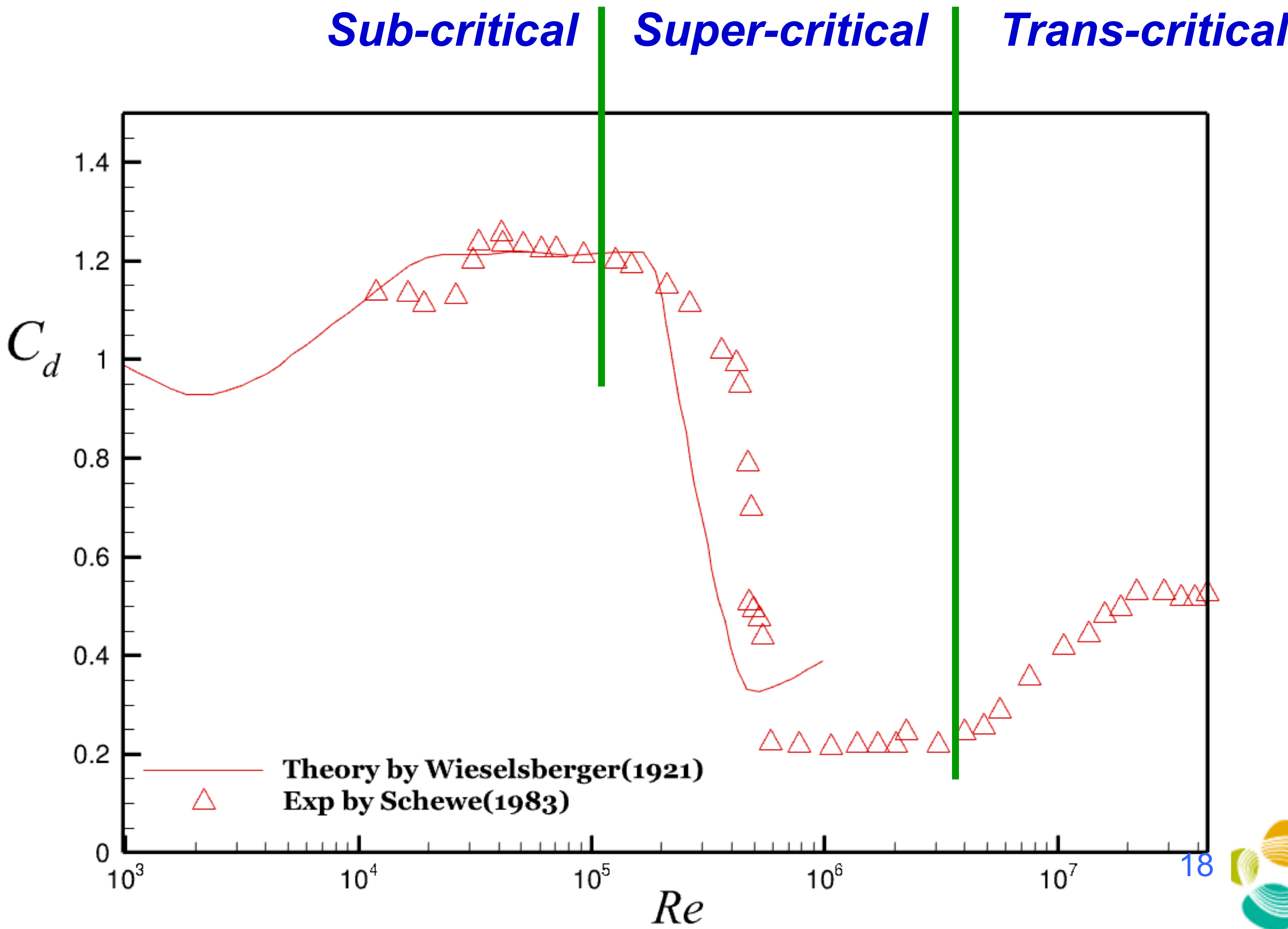
SC: Drag Coefficient



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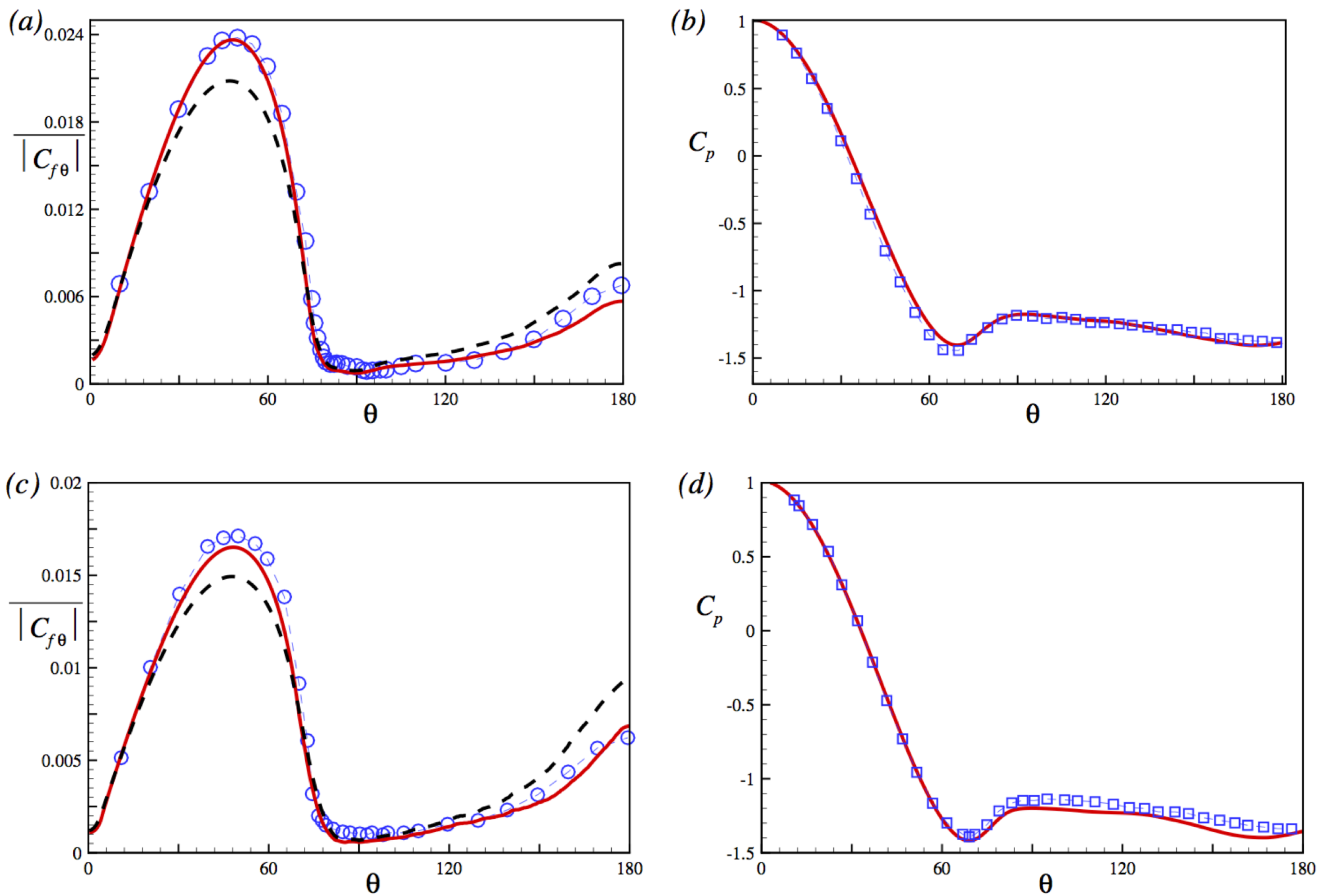
SC: Sub-critical cases

Re=5x10^4

Re=10^5



- *Passively using wall-model ODE gives best results when mesh is not fine enough*

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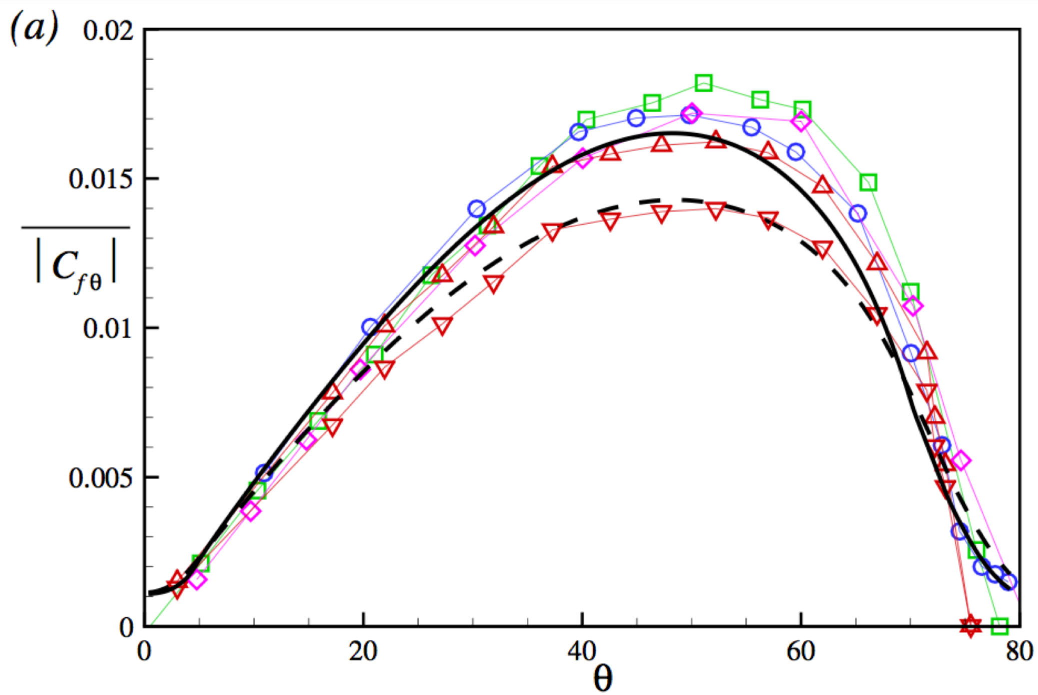
SC: Re=10^5



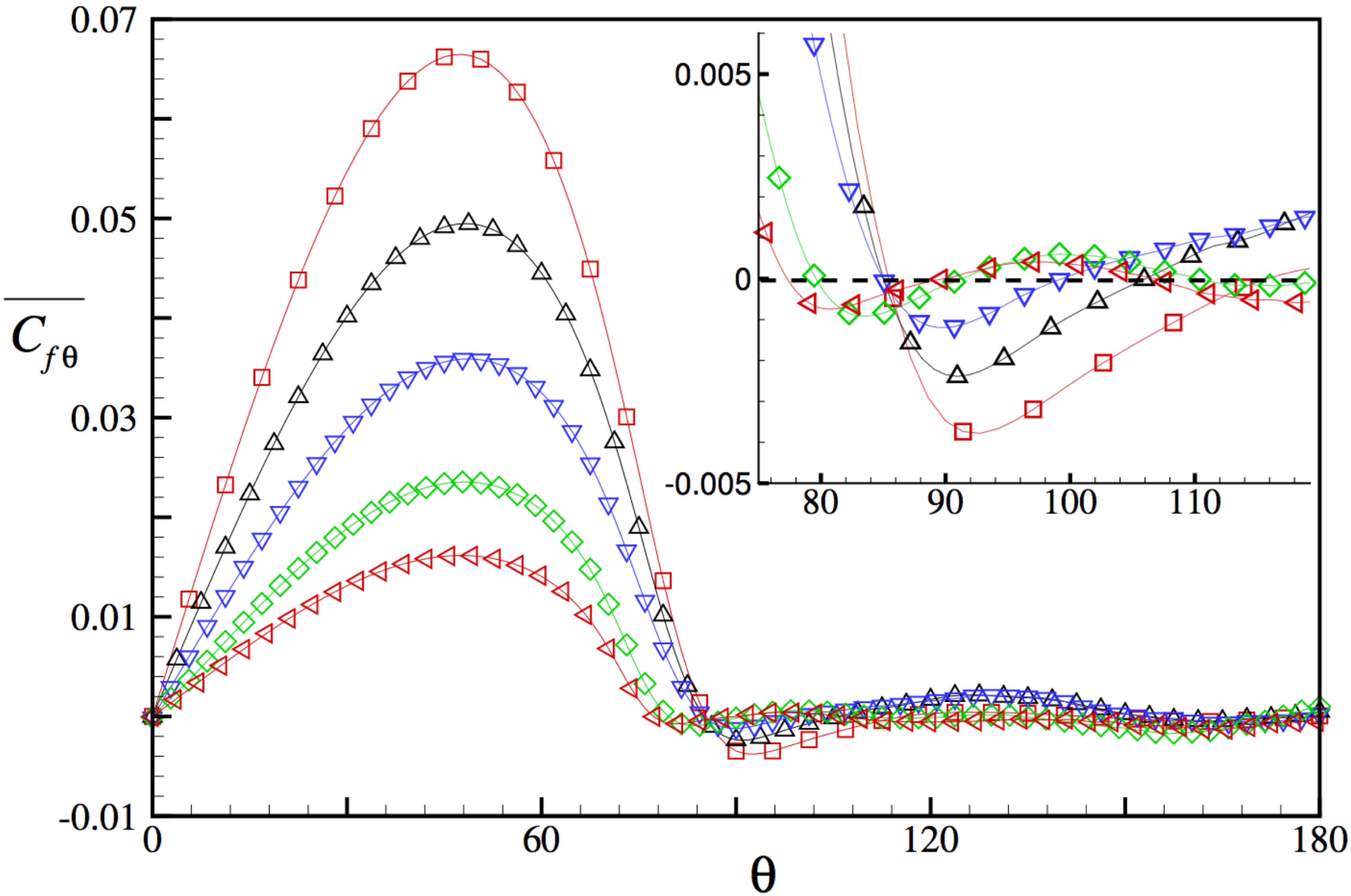
Exp by Achenbach (1968)
Exp by Son & Harraty (1969)
Exp by Giedt (1951)
Theory by Thom (1928)
using ODE

Diagnosed via momentum conservation law

Exp by Thom (1928)
velocity derivative

Diagnosed via velocity component

SC: Separation: sub-critical cases



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Zero crossing indicates separation/reattachment

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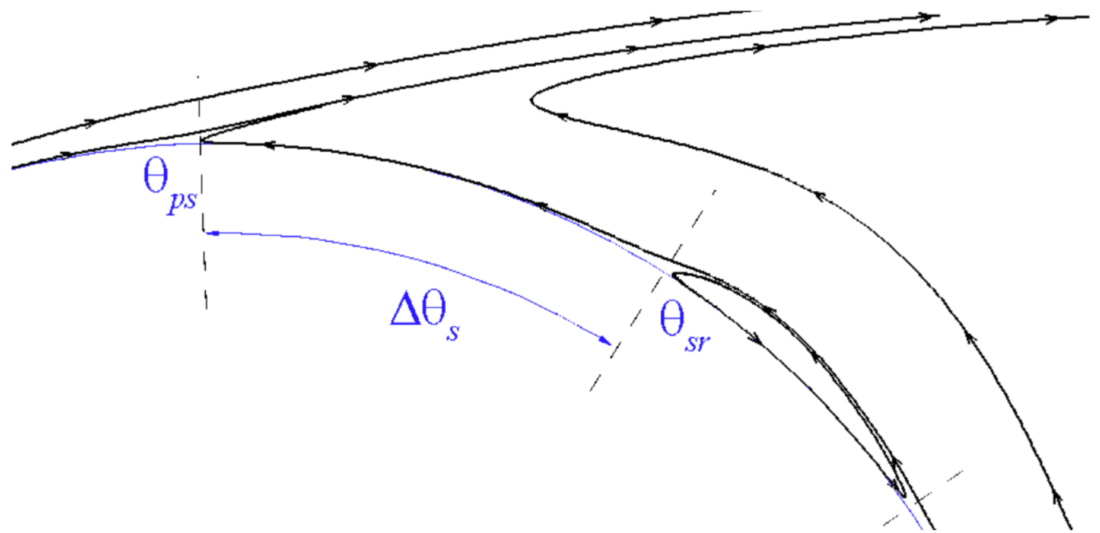
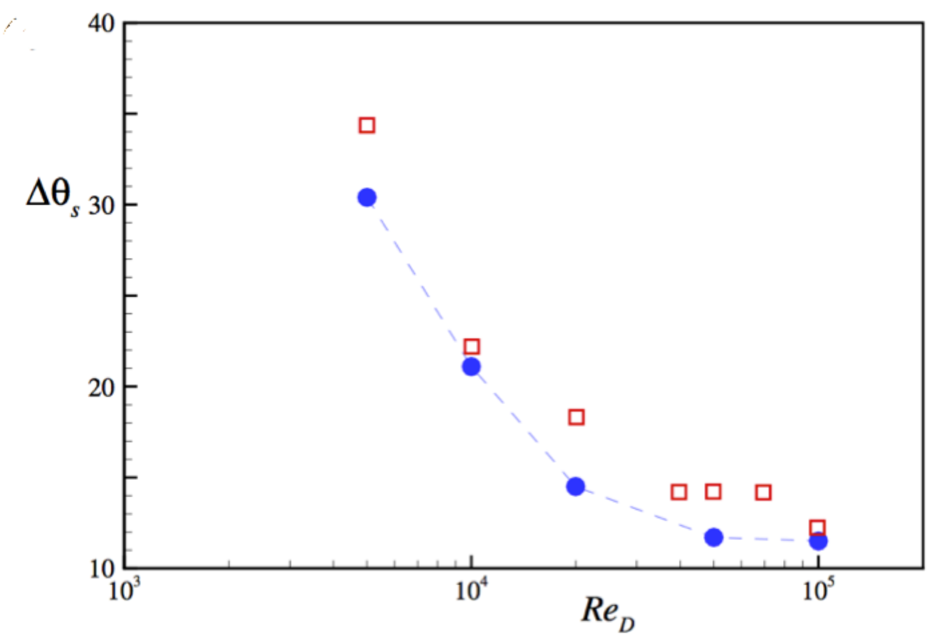
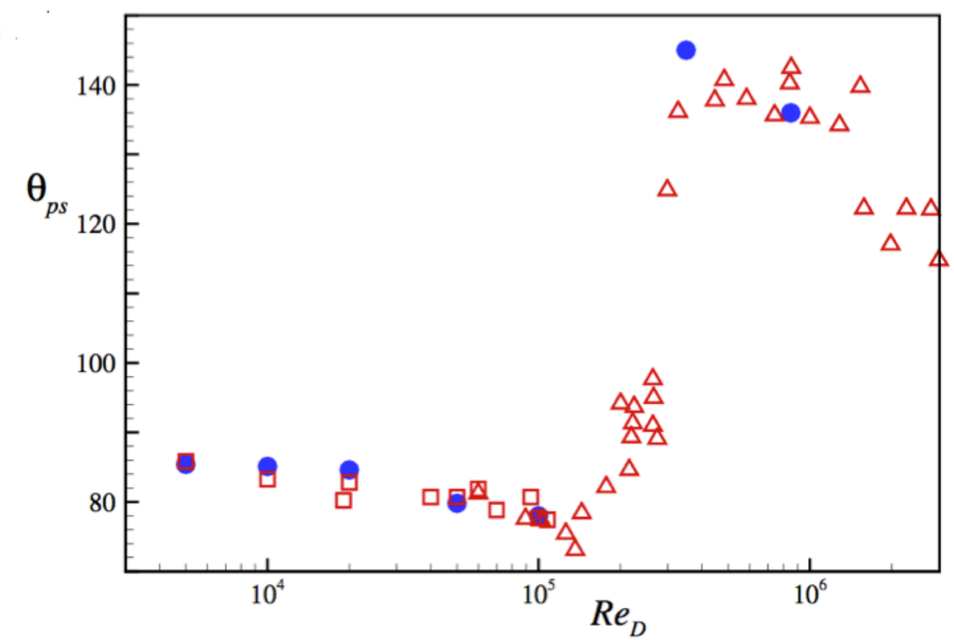
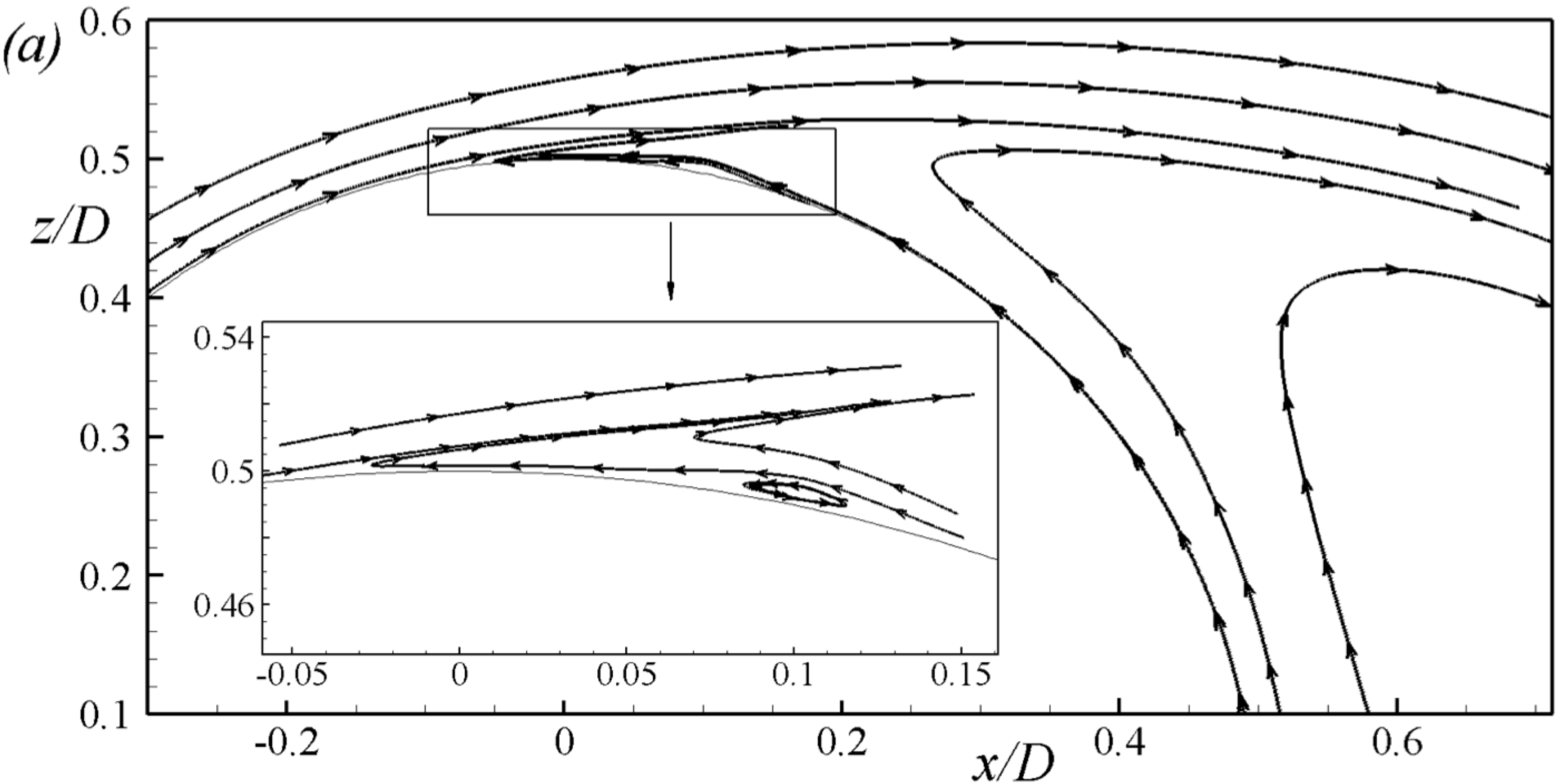
SC: Separation: sub-critical cases





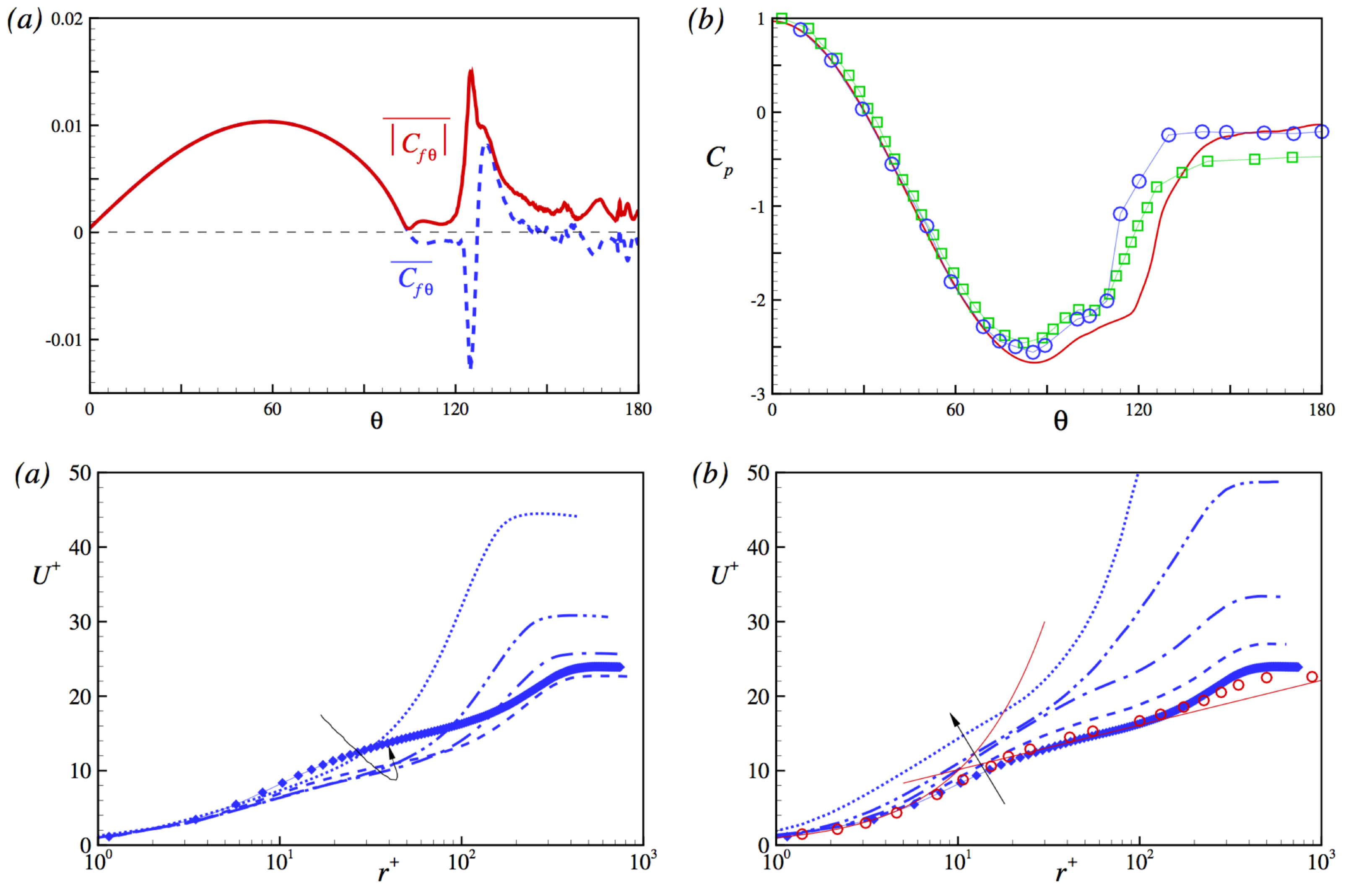


SC: Separation: sub-critical case $Re=10^5$



Discovery through simulation

SC: Re = 3.5 x 10^5



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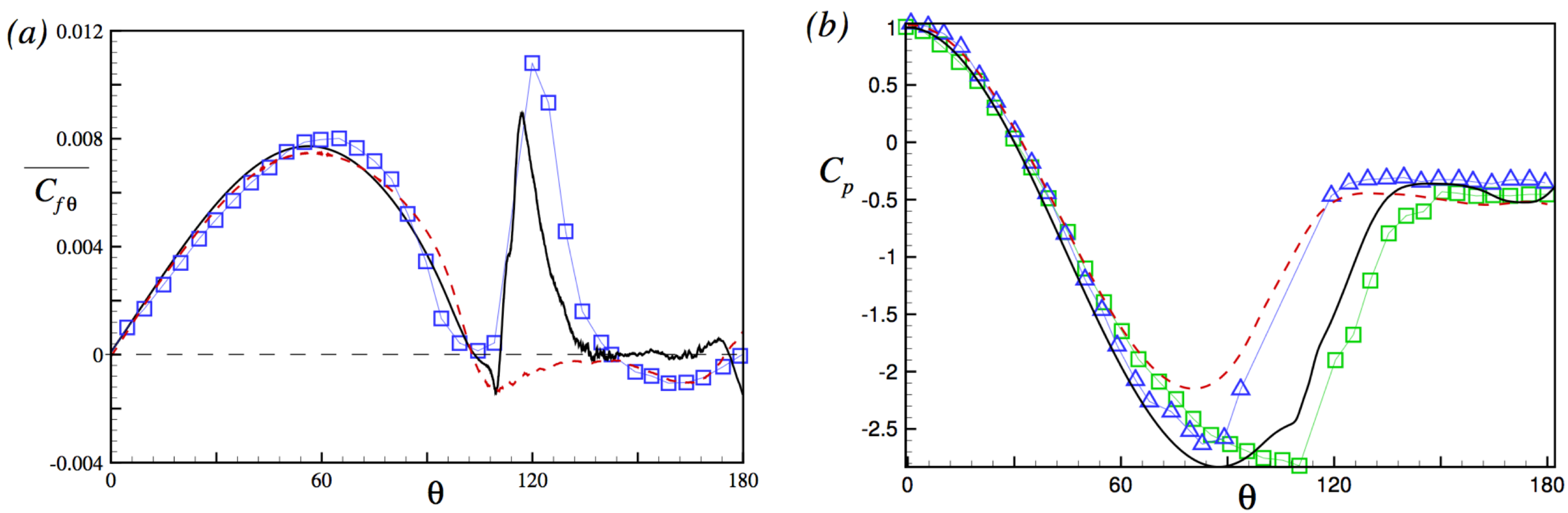
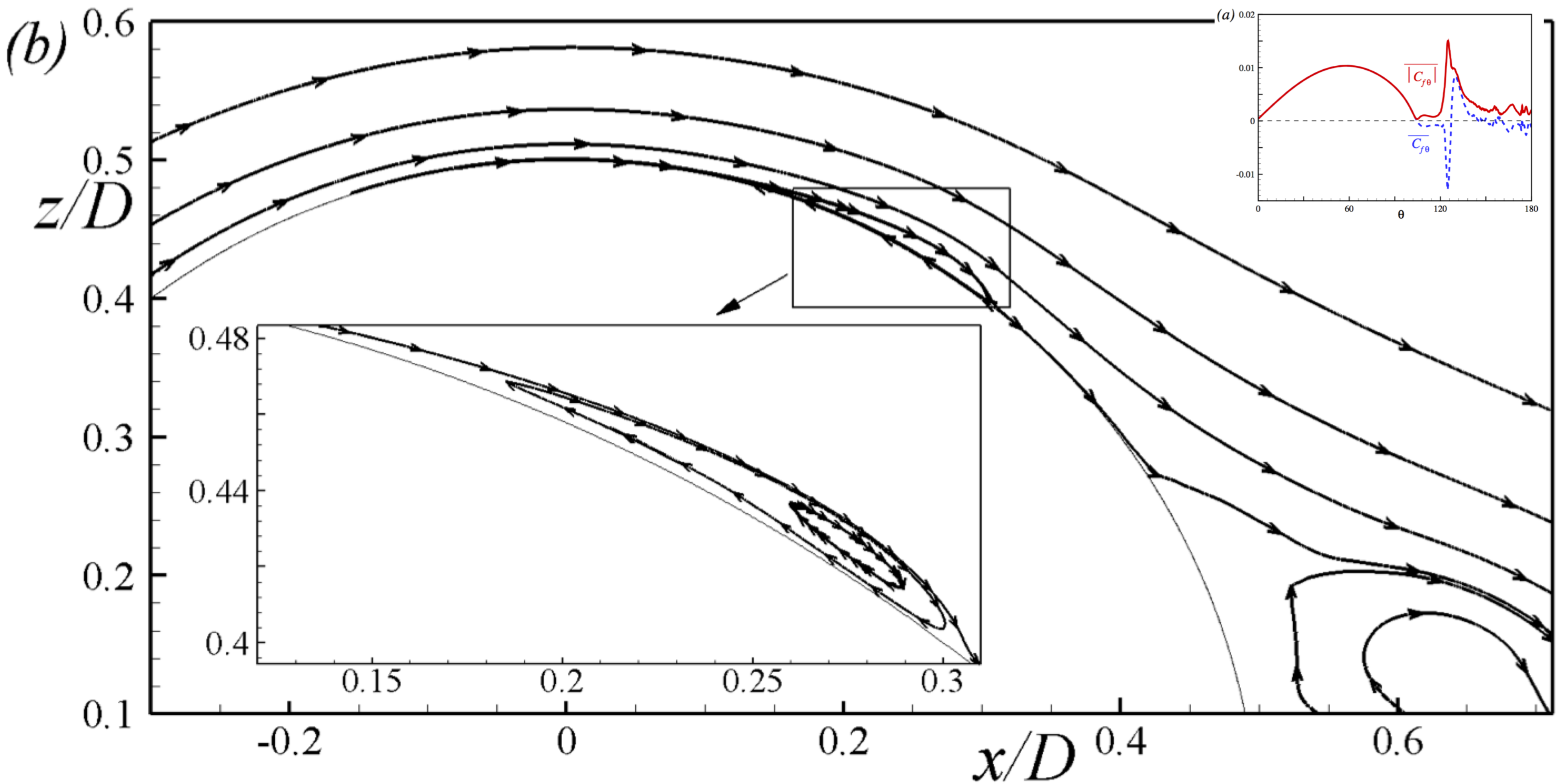
SC: Re = 8.5 x 10^5

- Coarse mesh: 2048 x 512 x 192
- Fine mesh: 8192x1024x256
- Agreement with Achenbach's experiments



- *Skin friction coefficient*
- *Pressure coefficient*

SC: Separation, super-critical case $Re= 3.5x10^5$



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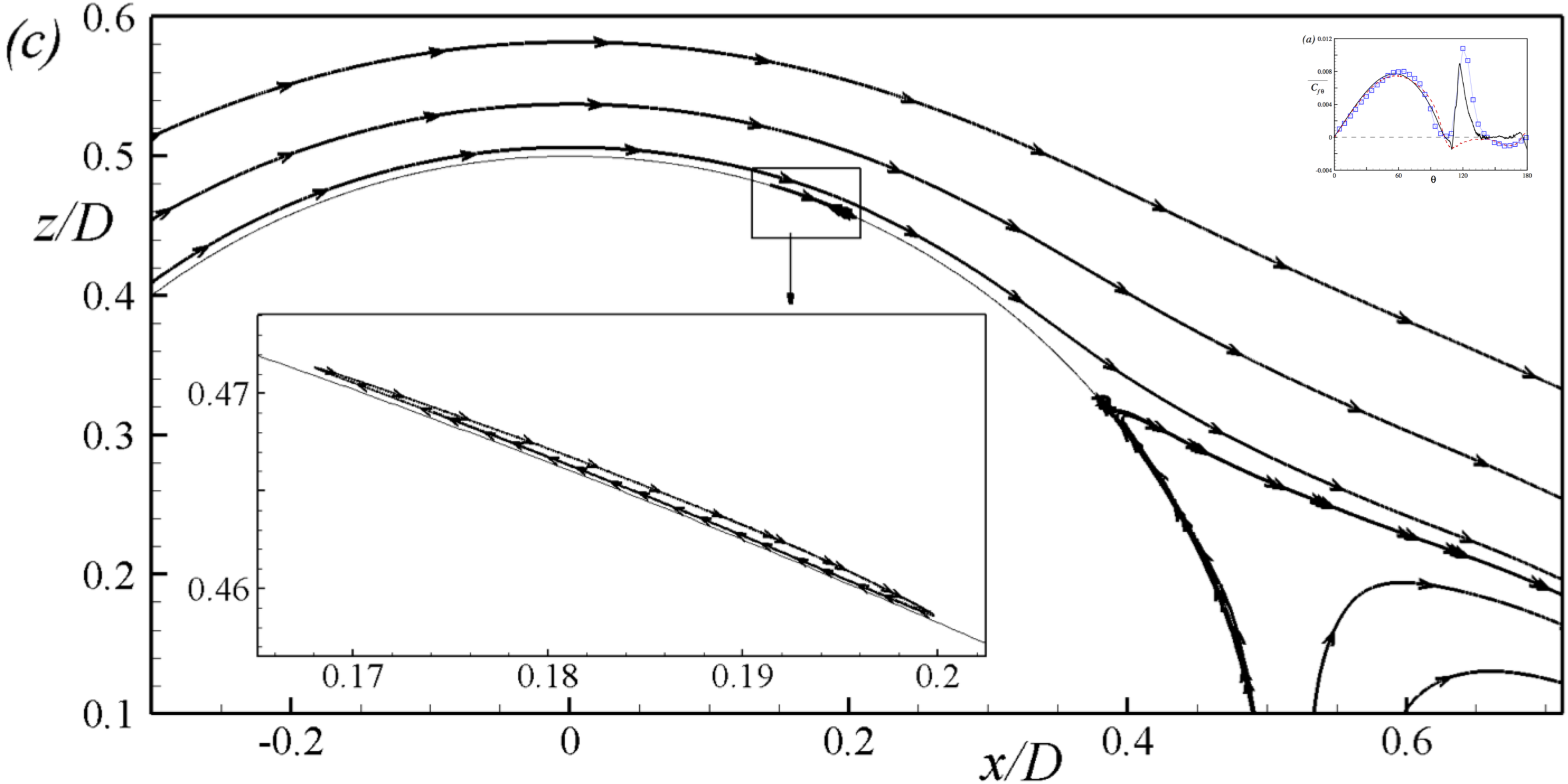
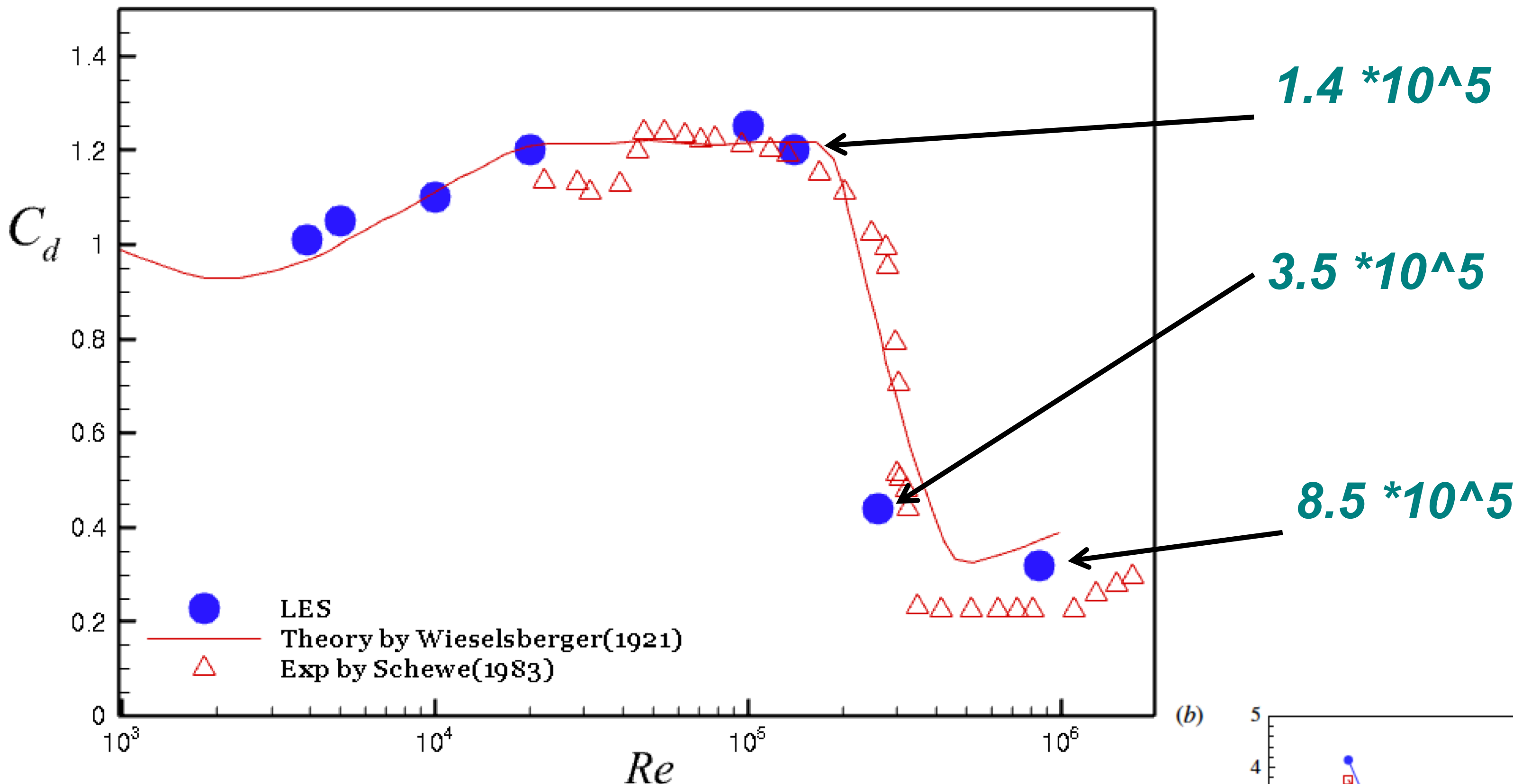
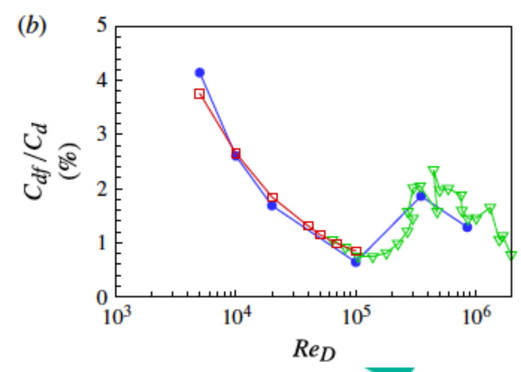
SC: Separation, super-critical case $Re= 8.5x10^5$



SC: Drag Coefficient

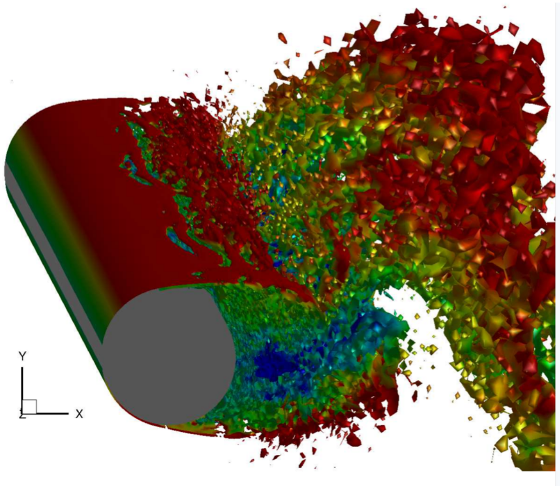


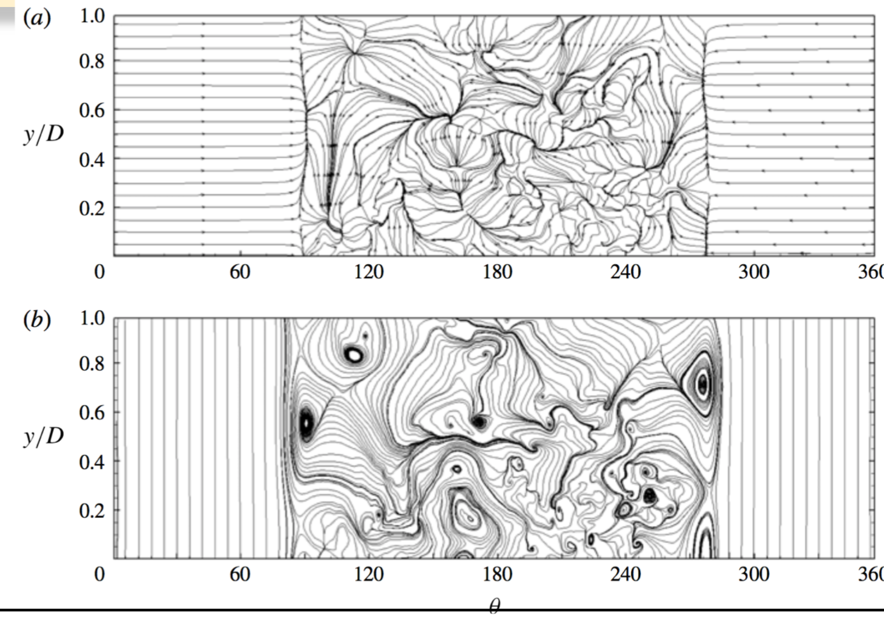


SC: Flow past a cylinder

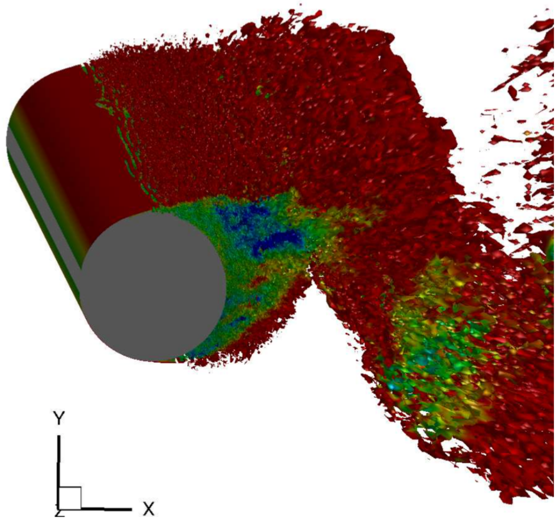
Cheng, Pullin, Samtaney, Zhang & Gao, JFM，2017

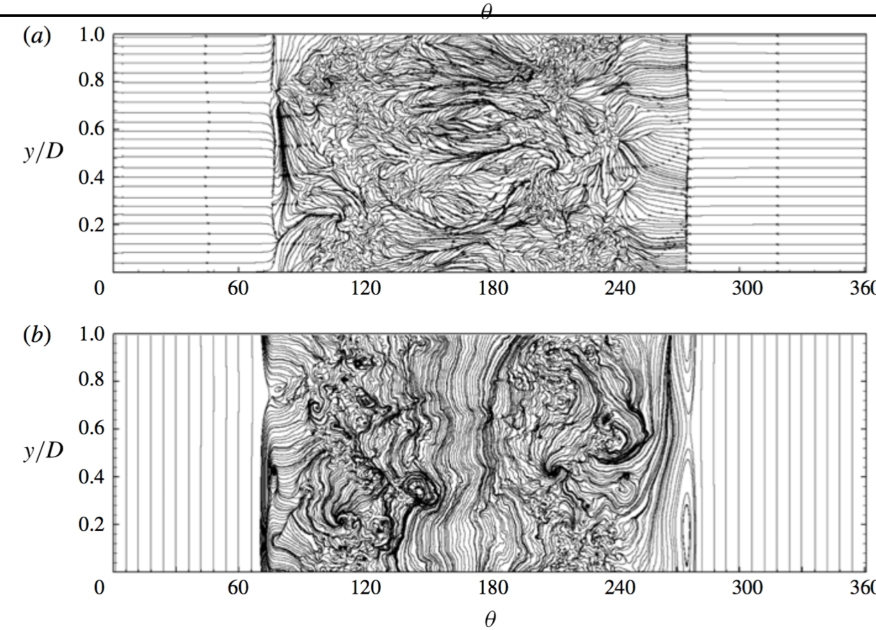
Re=10^{4}





Re=10^{5}





Discovery through simulation

SC: Flow past a cylinder

- Instantaneous flow:
  - From Subcritical to supercritical

    The interaction between the shear layer induced by the primary separation and separation/reattachment bundles

- Mean flow
  - From Subcritical to supercritical

    The disappearance of secondary separation bubble and appearance of prior separation bubble
  - From supercritical to transcritical

    The disappearance of prior separation bubble

- Hypothesis: dynamic interaction between primary separation and the unsteady secondary separation could be a more general mechanism for drag crisis in bluff body flow.

Discovery through simulation

GR: Experiments: from high Re to low Re

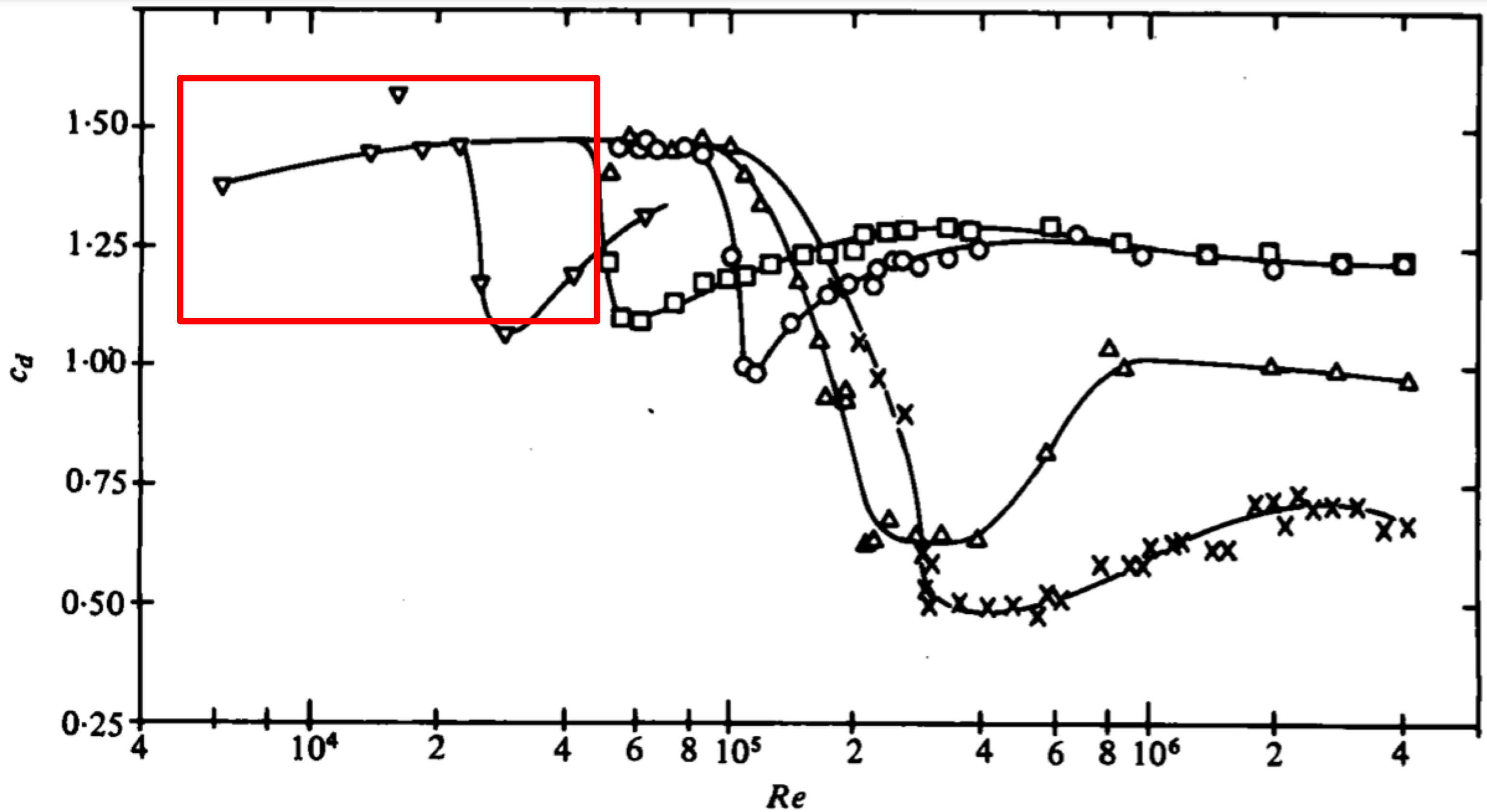


Figure 3. Drag coefficient of the single cylinder in cross flow at various surface roughness parameters k_s/d: ×, smooth; △, 75×10^{-5}; ○, 300×10^{-5}; □, 900×10^{-5}; ▽, 3000×10^{-5}.

- Wall resolved LES of a cylinder with non-smooth surface

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GR: From experiment to grooved wall simulation

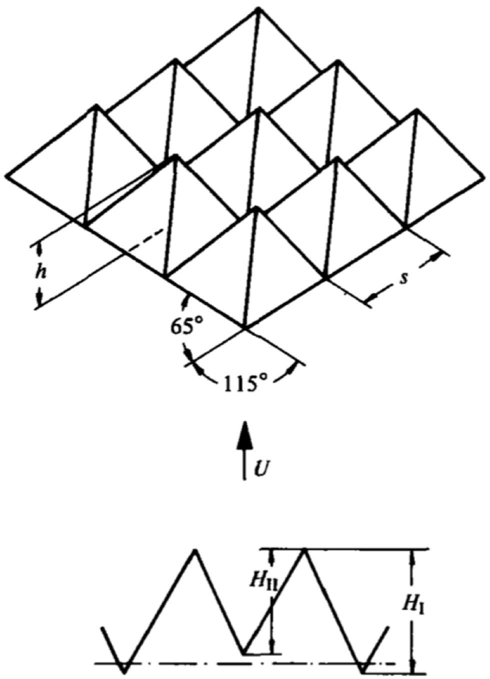
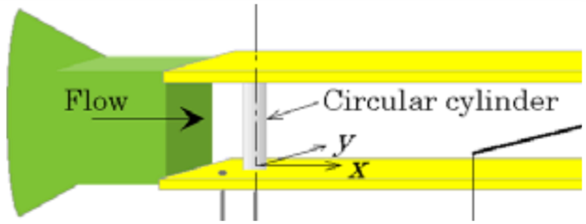
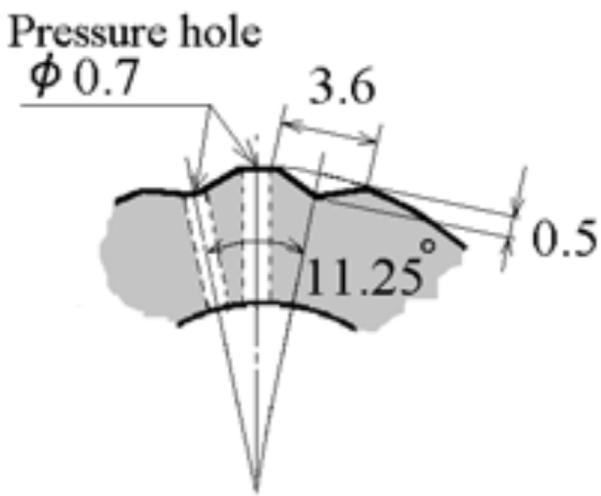
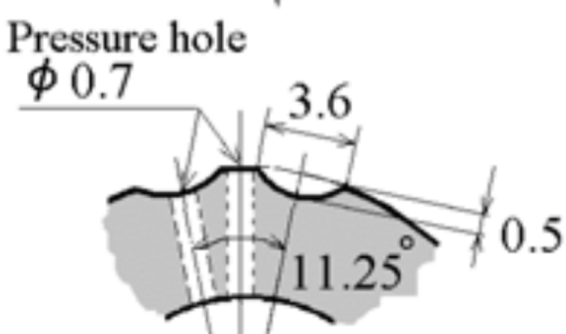


FIGURE 2. Roughness pattern.

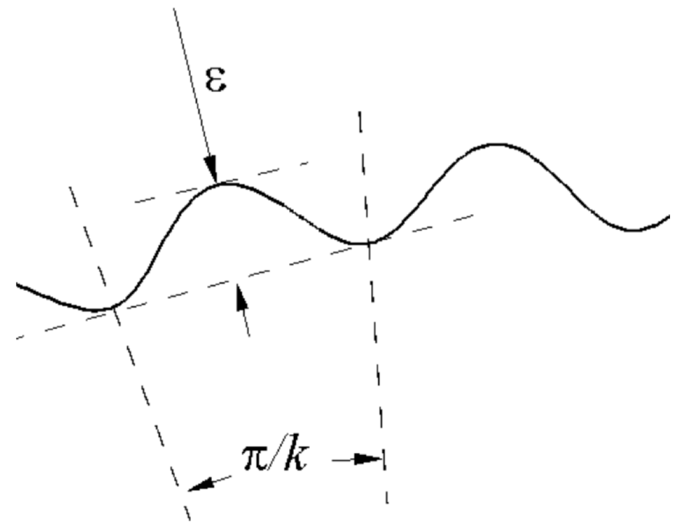
H_I (mm)	0·75–0·825
H_{II} (mm)	0·60–0·675
s (mm)	2·1
k_s/d	3000×10^{-5}







- Simulation setup

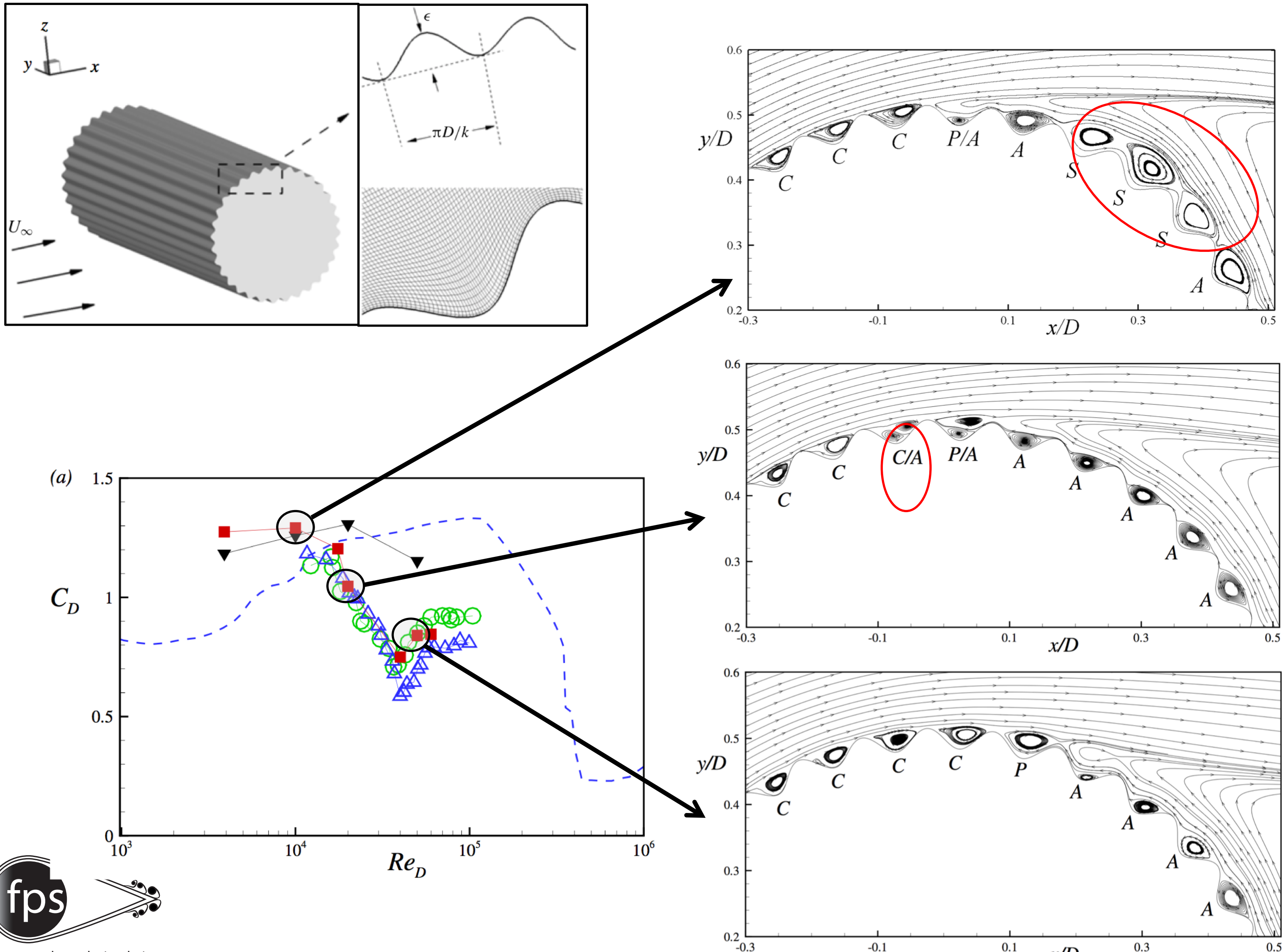


$$k = 32$$

$$\epsilon = 1/k$$

GR: Flow past a grooved cylinder

Cheng, Pullin, Samtaney, JFM，2018



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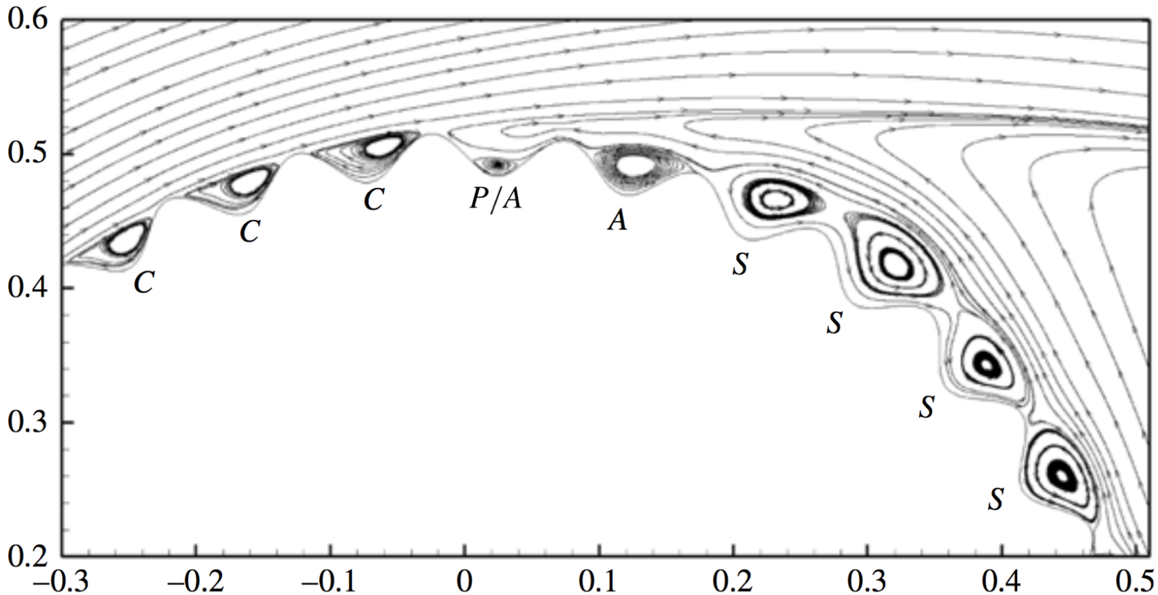
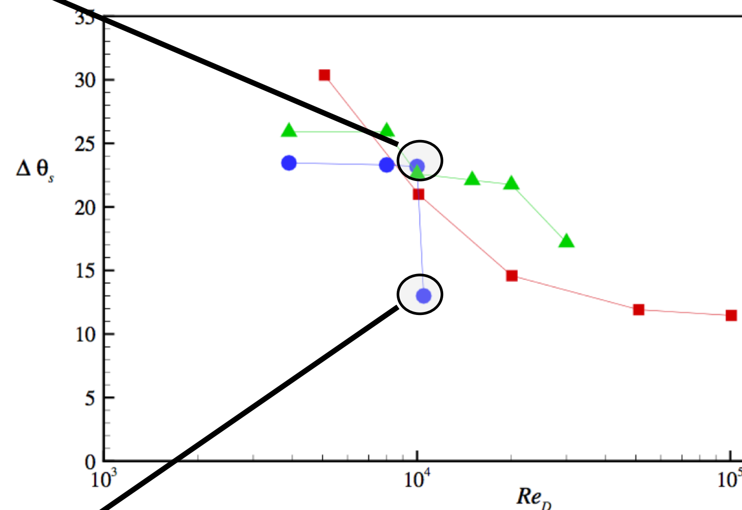
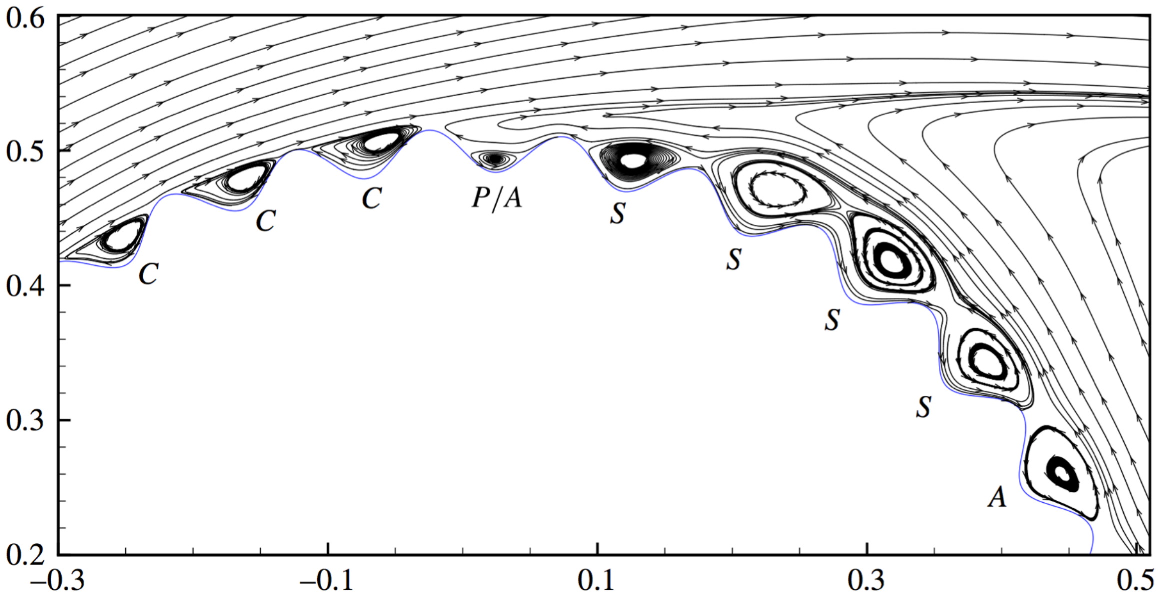
GR: Secondary separation bubble

Cheng, Pullin, Samtaney, JFM，2018

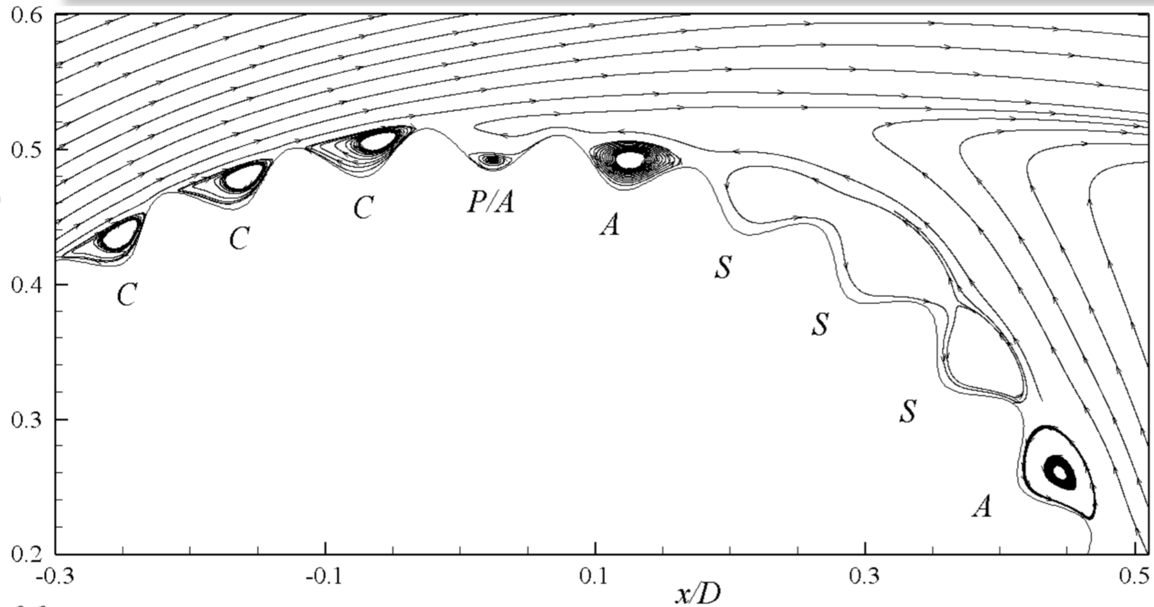


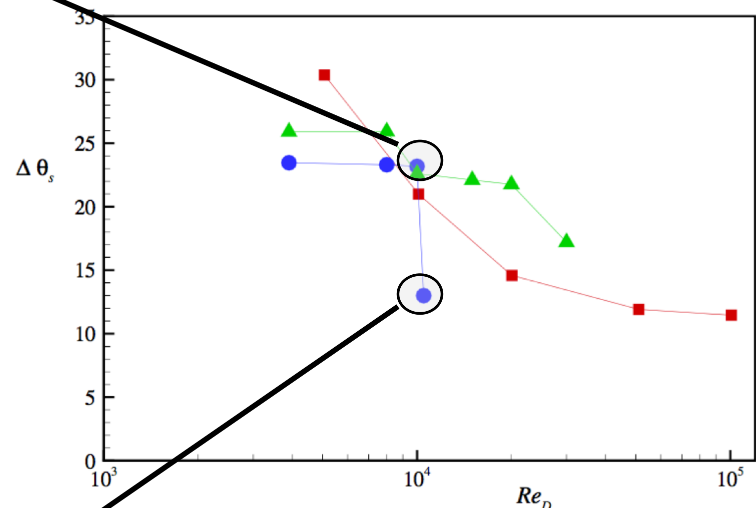


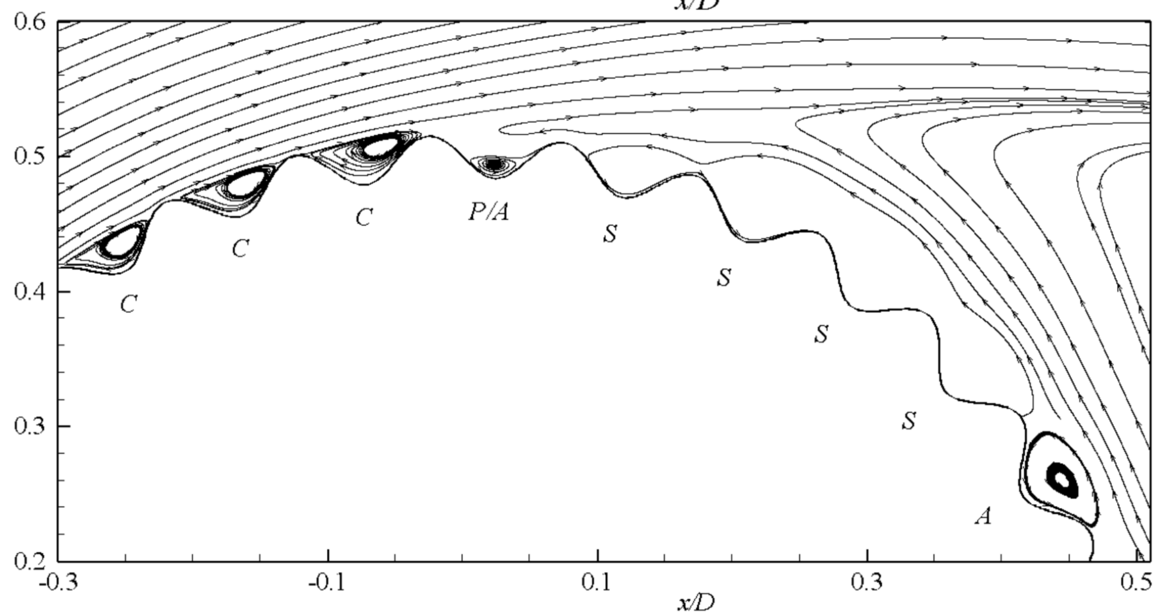


GR: Secondary separation bubble

Cheng, Pullin, Samtaney, JFM，2018



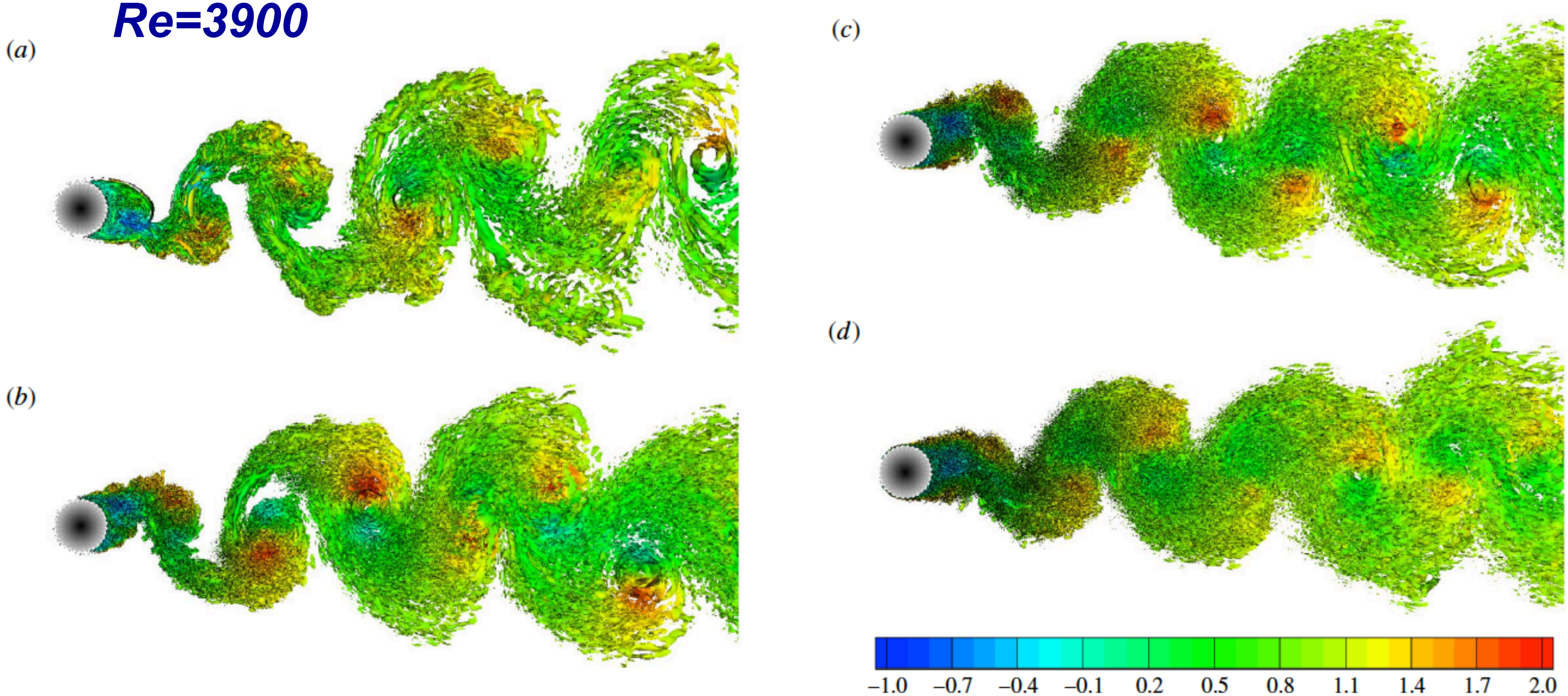




GR: Instantaneous isosurfaces of Q

Re=3900

Re=$2x10^4$

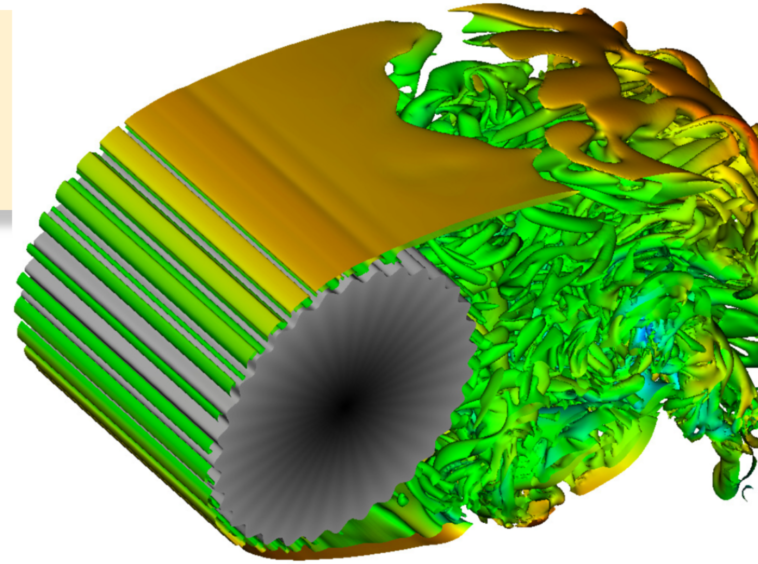


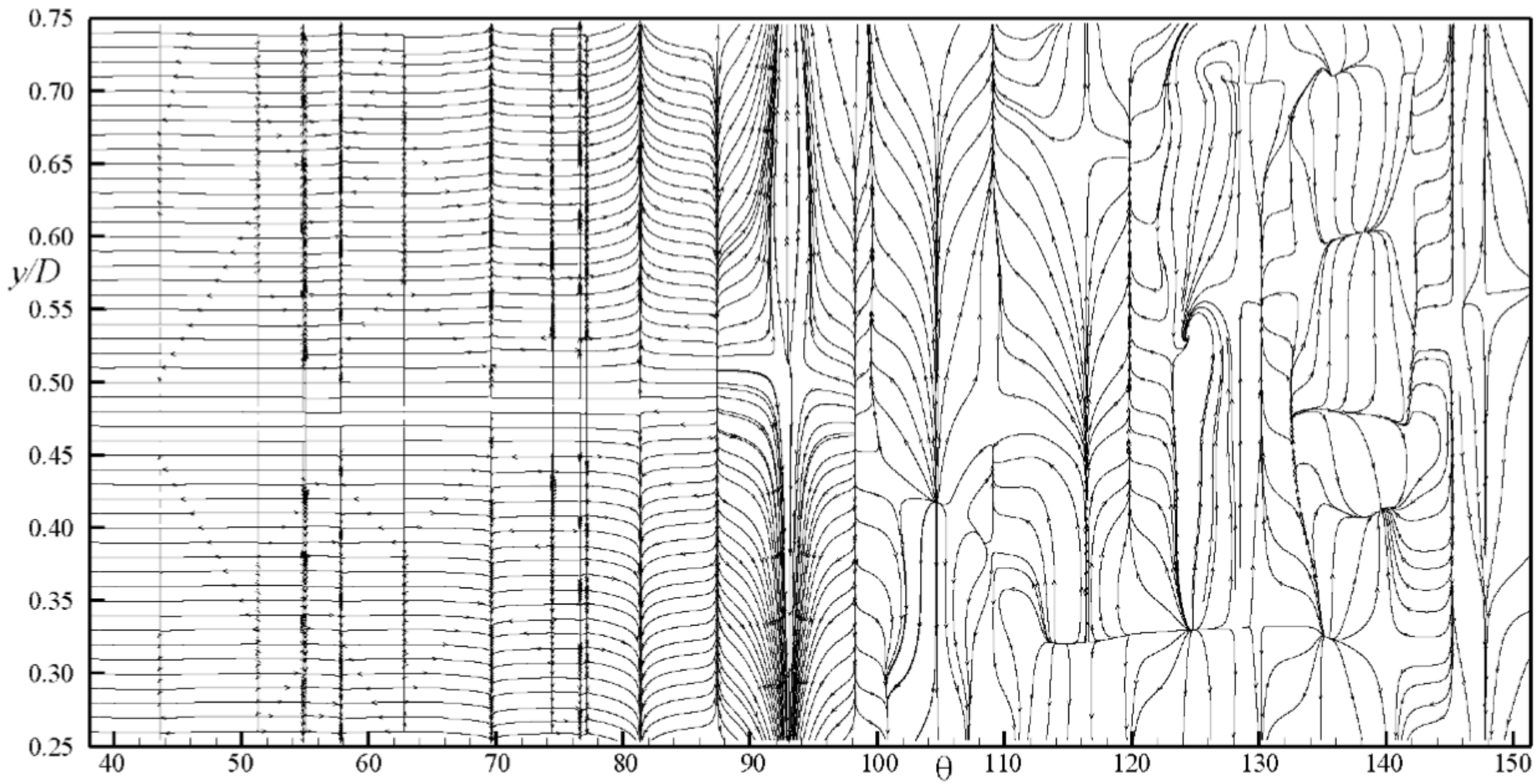
Re=10^4

Re=$5x10^4$

GR:

$Re_D = 3.9 \times 10^3$

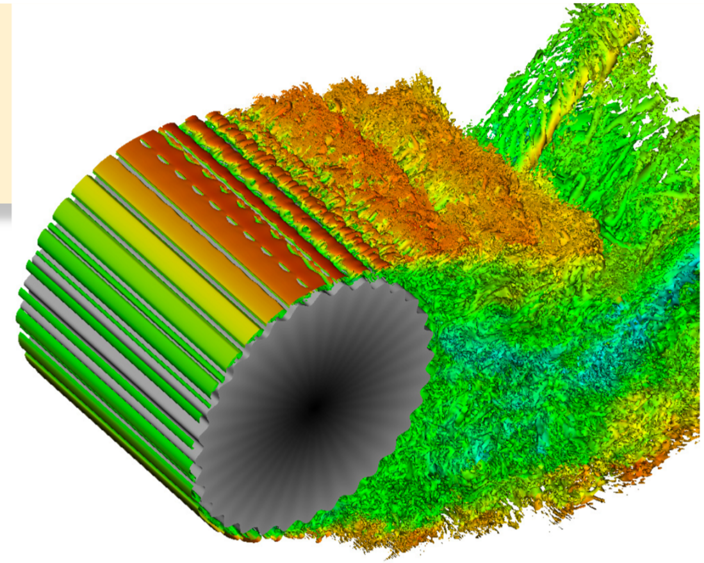


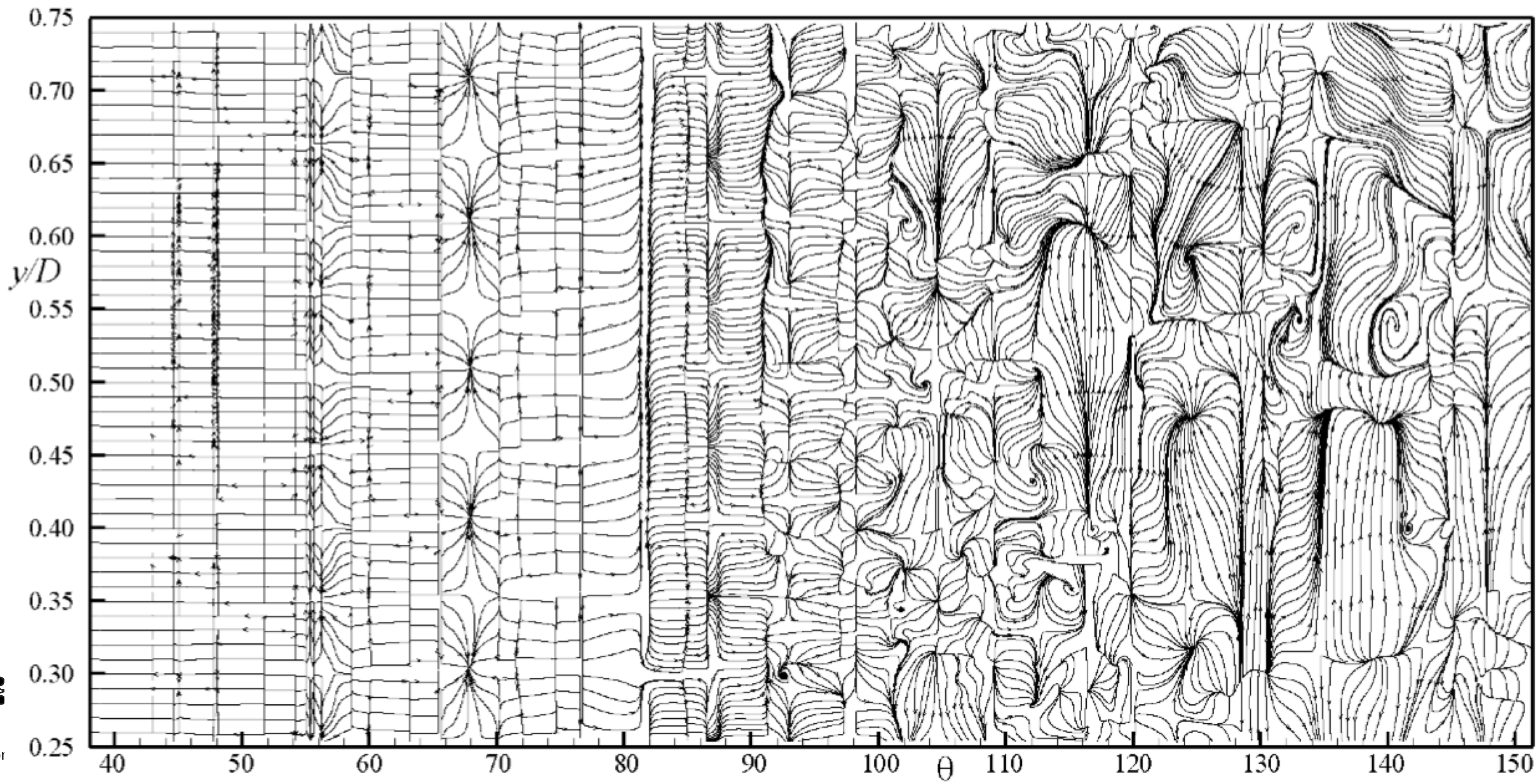


Discovery through simulation

GR:

$$Re_D = 1 \times 10^4$$

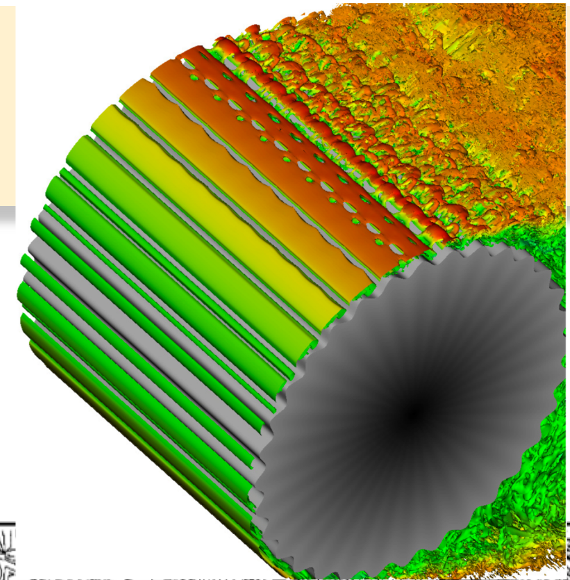


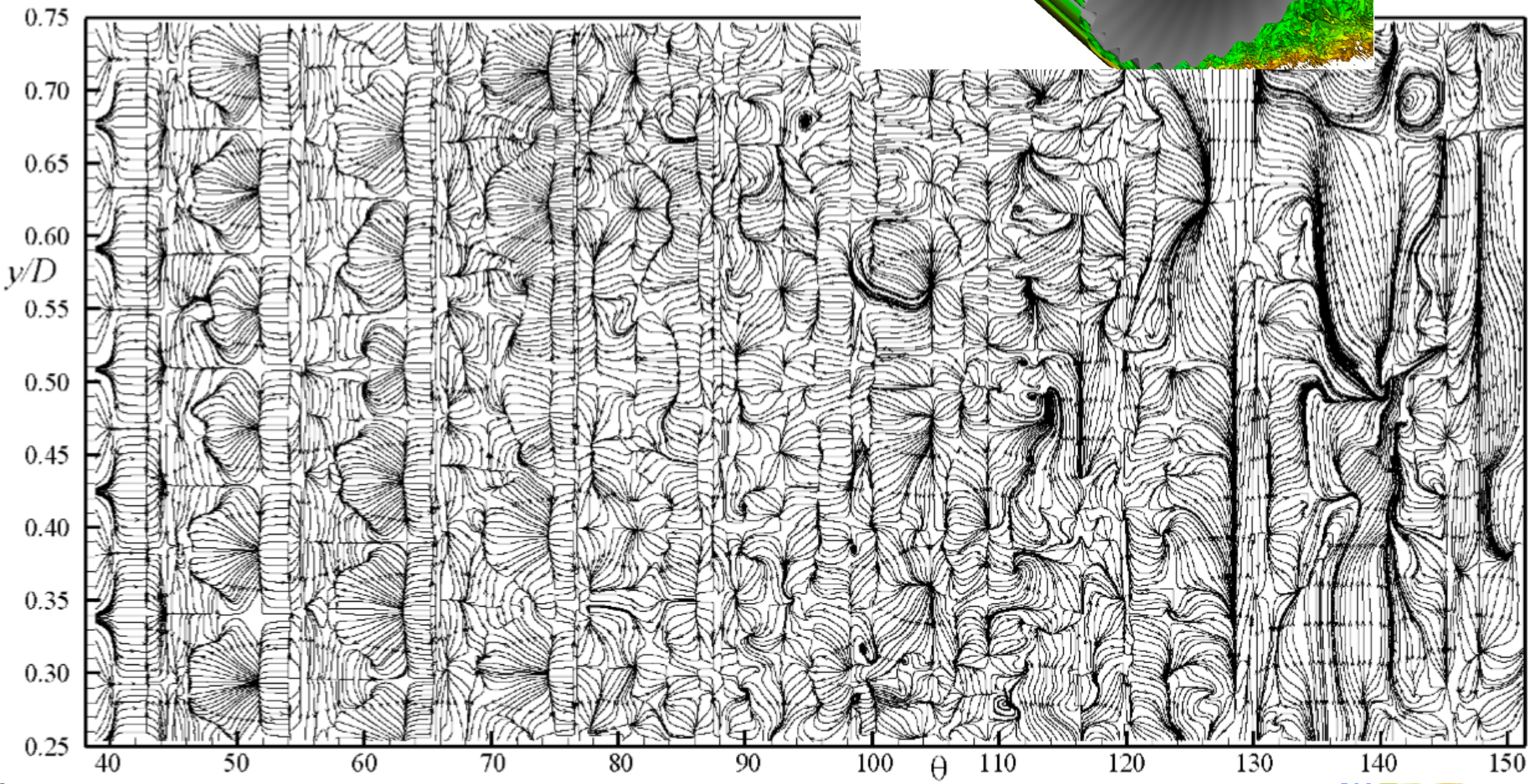


Discovery through simulation

GR:

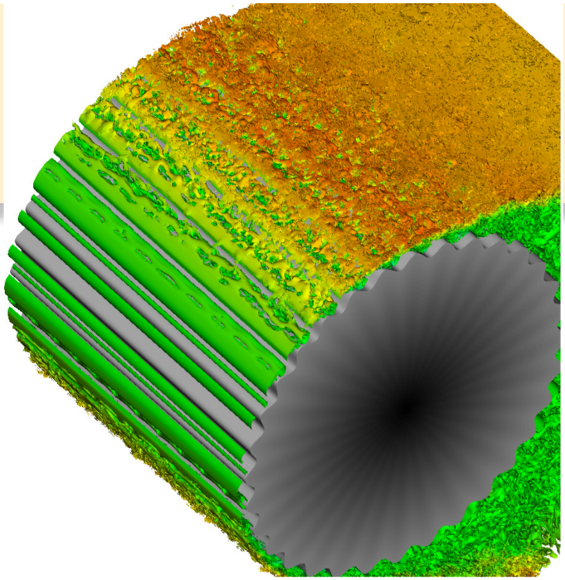
$$Re_D = 2 \times 10^4$$

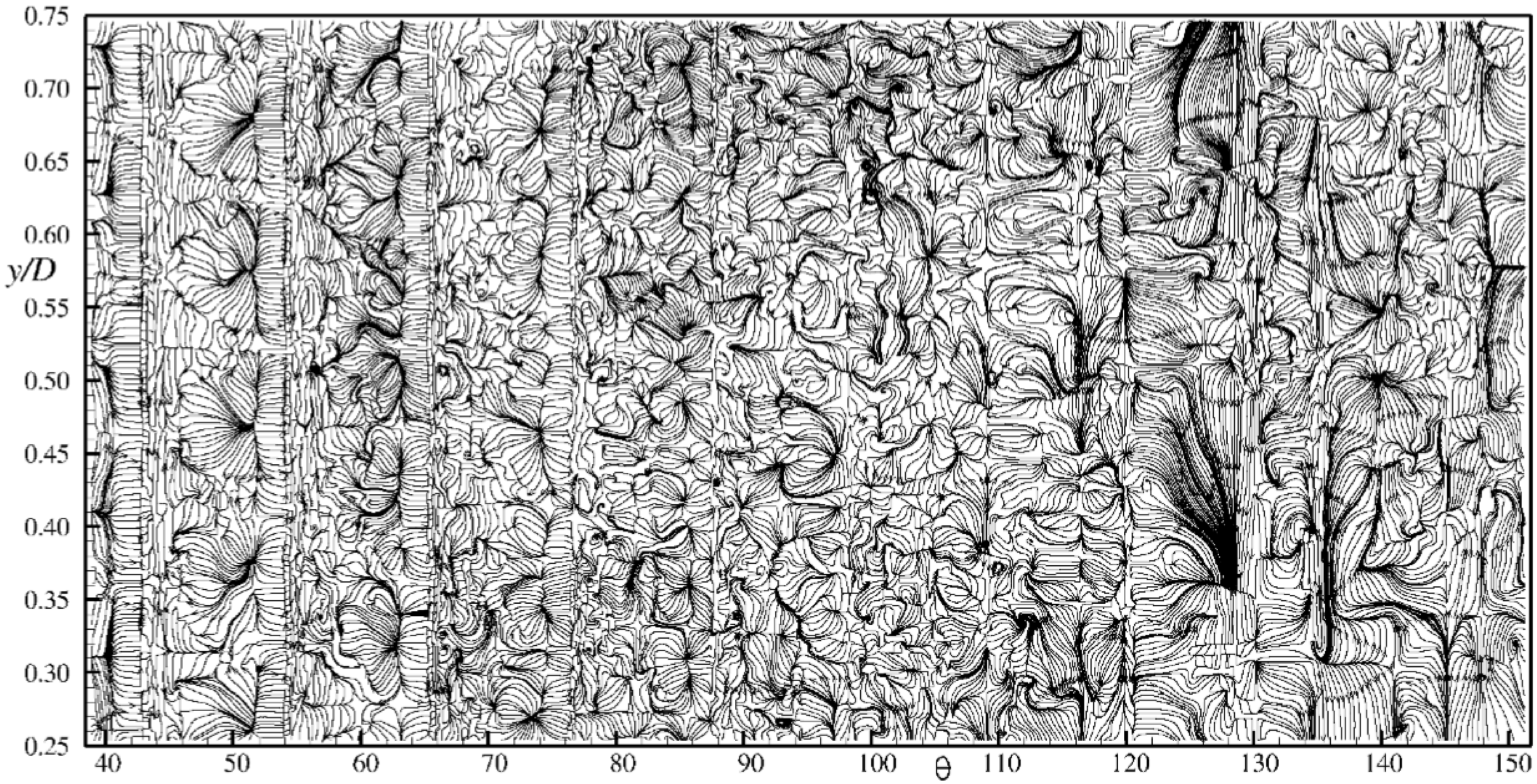




GR:

$$Re_D = 5 \times 10^4$$





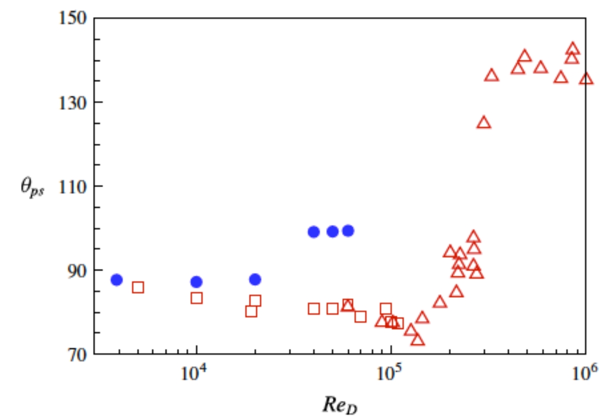
fps
Discovery through simulation

Cylinder + Grooved cylinder

- Cylinder flow

Hypothesis: drag crisis is due to dynamic interaction between primary separation with unsteady secondary separation.

  – Mean flow: Secondary separation bubble
  – Instantaneous: separatrices and diverging bundles with small-scale separation/reattachment cells



- Grooved Cylinder flow

Confirm: drag crisis is also due to dynamic interaction between primary separation with unsteady secondary separation.

  – Mean flow: Secondary separation bubble
  – Instantaneous: separatrices and diverging bundles with small-scale separation/reattachment cells

Discovery through simulation

KAUST

Smooth Cylinder + Grooved cylinder

- Smooth Cylinder flow

Hypothesis: drag crisis is due to dynamic interaction between primary separation with unsteady secondary separation.

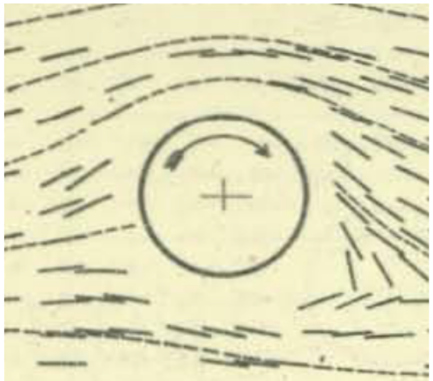
  - Mean flow: Secondary separation bubble
  - Instantaneous: separatrices and diverging bundles with small-scale separation/reattachment cells
  - The secondary separation bubble moves upstream continuously

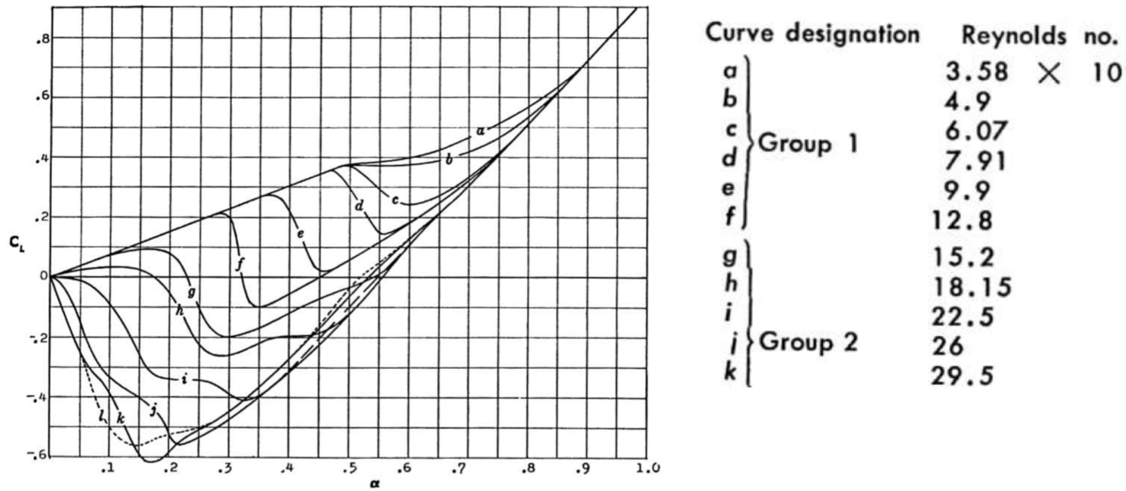
- Grooved Cylinder flow

Confirm: drag crisis is also due to dynamic interaction between primary separation with unsteady secondary separation.

  - Mean flow: Secondary separation bubble
  - Instantaneous: separatrices and diverging bundles with small-scale separation/reattachment cells
  - The secondary separation bubble moves upstream discontinuously

Background of Flow past a rotating cylinder



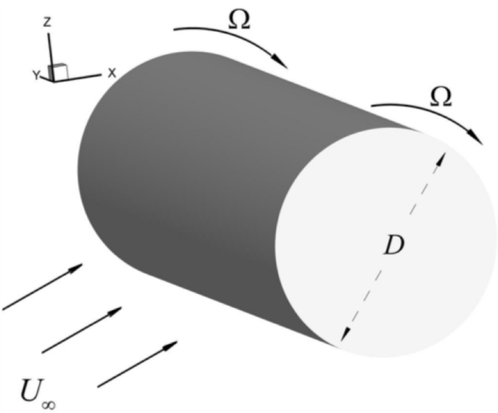


Discovery through simulation

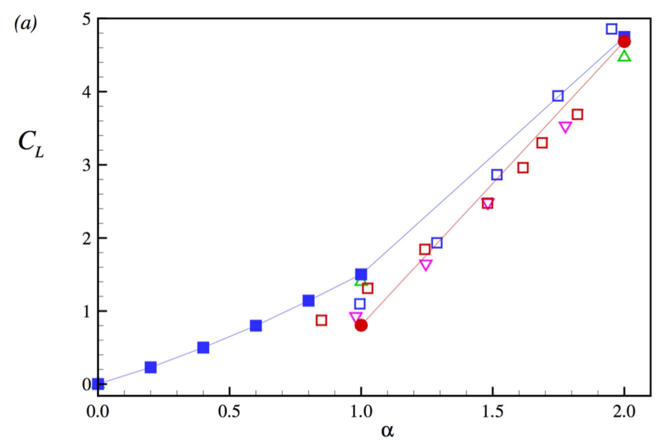
KAUST

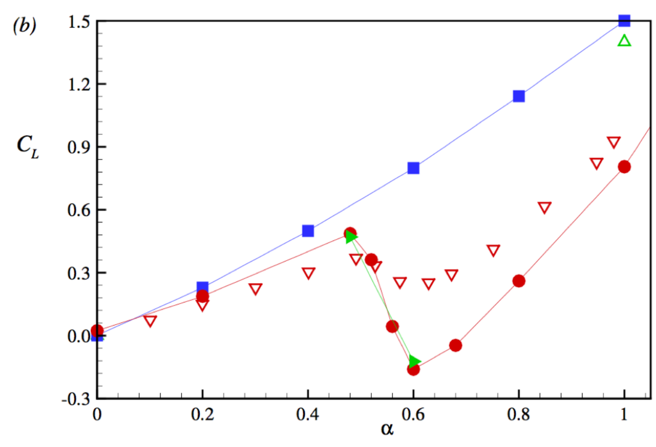
RC: Flow past a rotating cylinder

Cheng, Pullin, Samtaney, JFM 2018

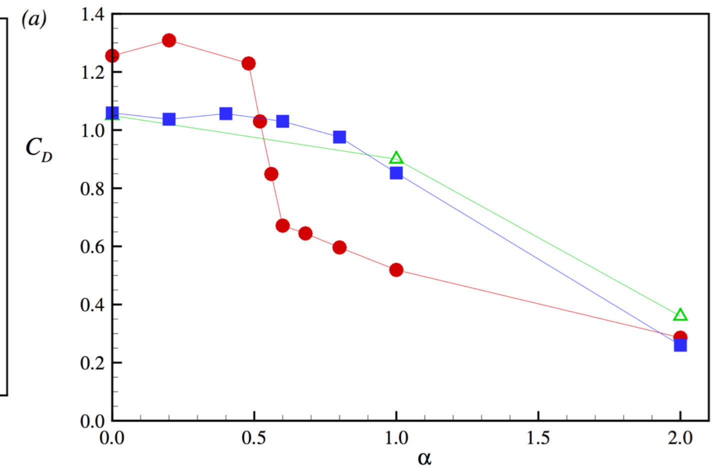


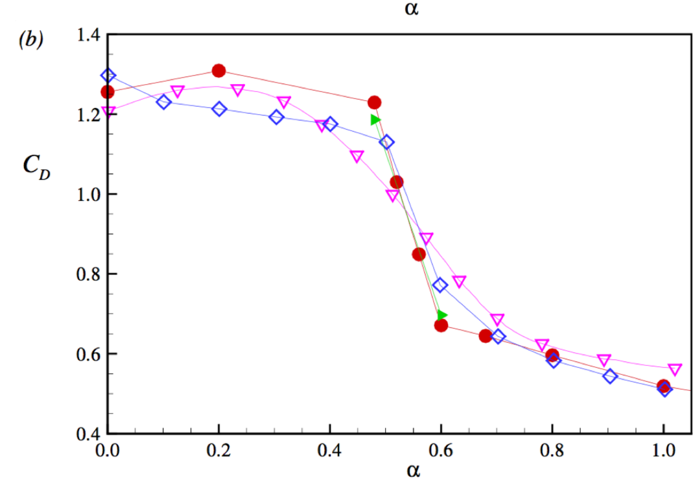
Lift Coefficient





Drag Coefficient



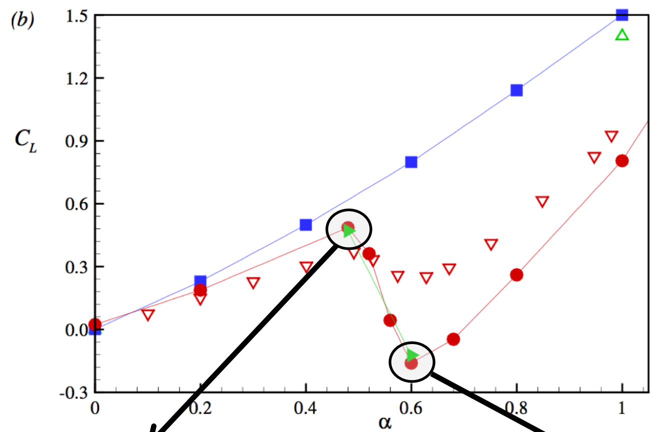


Discovery through simulation

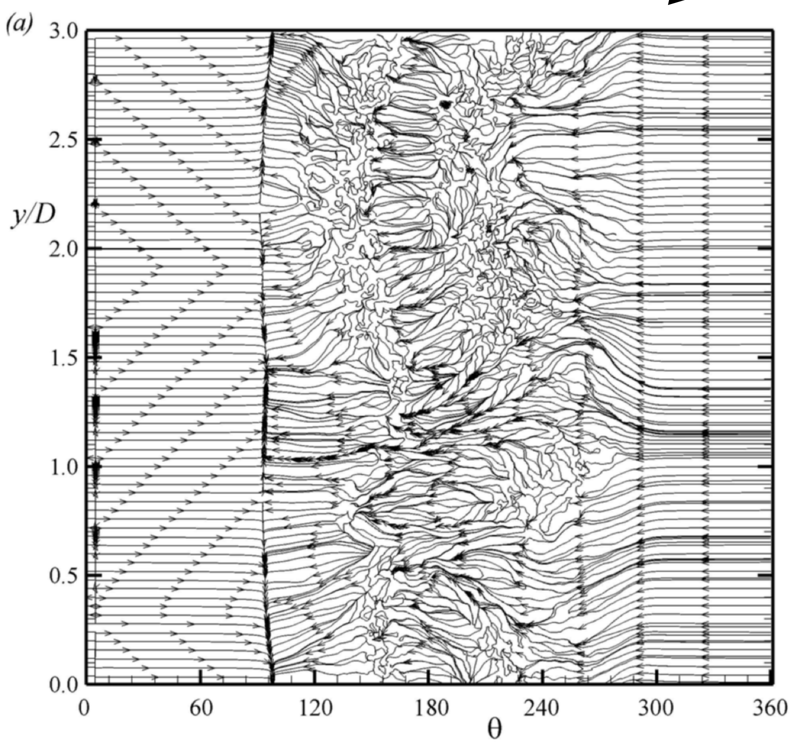
RC: Flow past a rotating cylinder

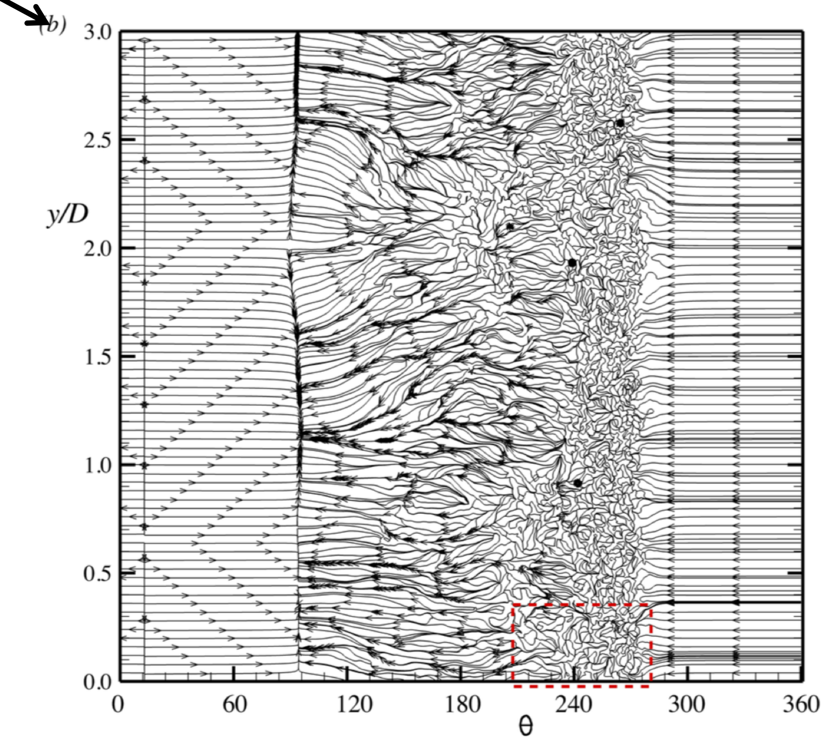
Cheng, Pullin, Samtaney, JFM 2018

Distributed small scale separation/reattachment cells



aggregated small scale separation/reattachment cells

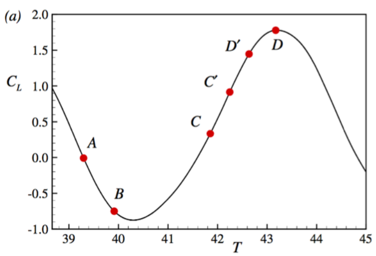


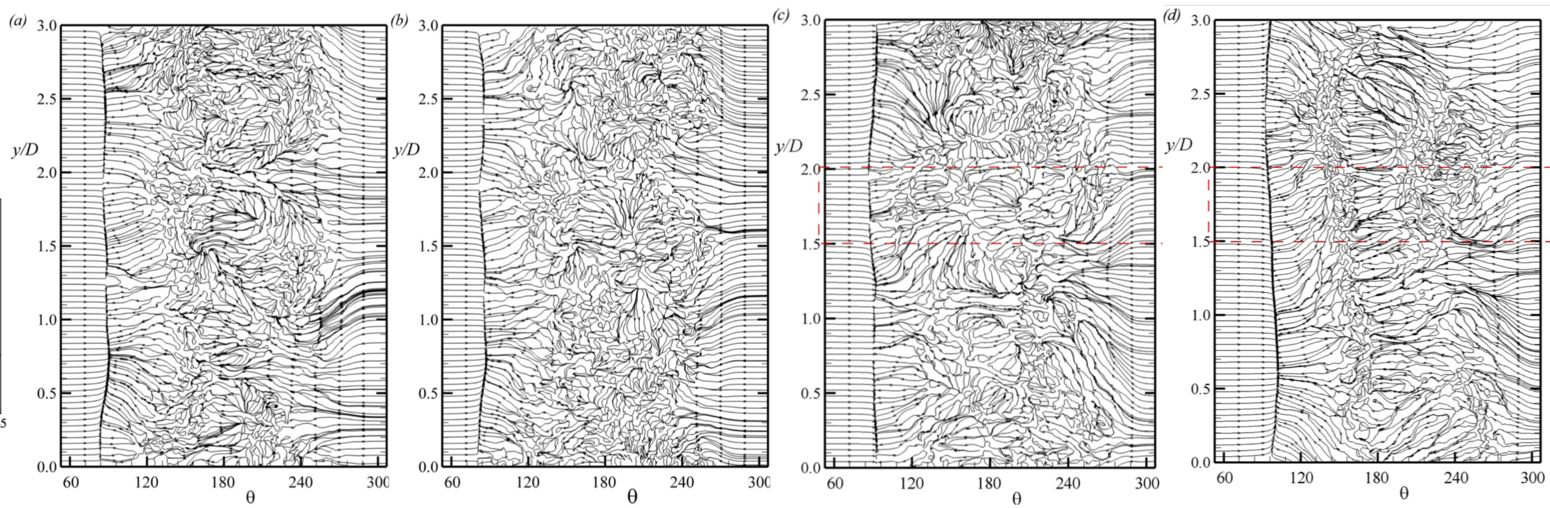


RC: Flow past a rotating cylinder

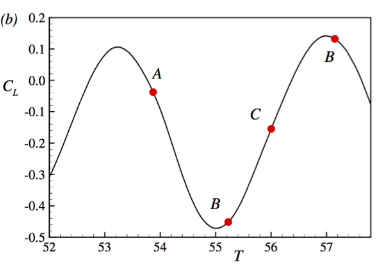
Cheng, Pullin, Samtaney, JFM 2018

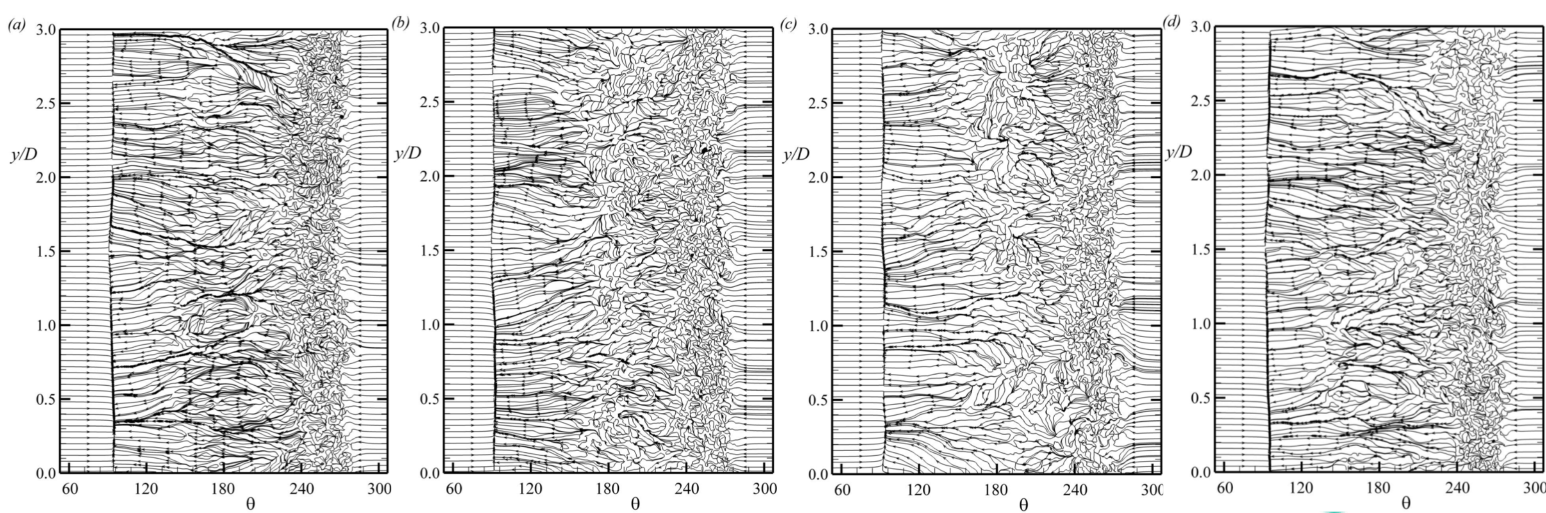
$\alpha=0.48$





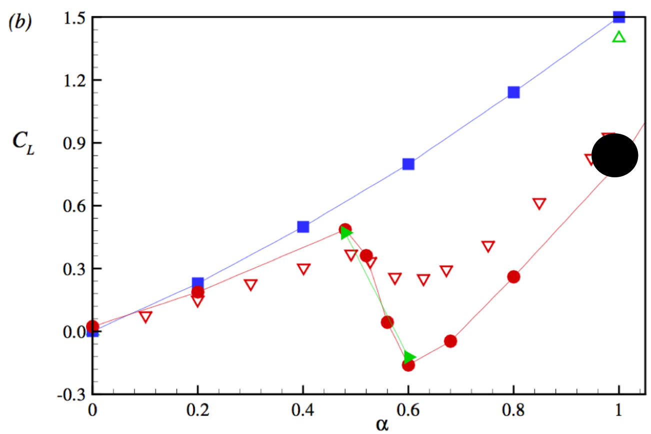
$\alpha=0.6$

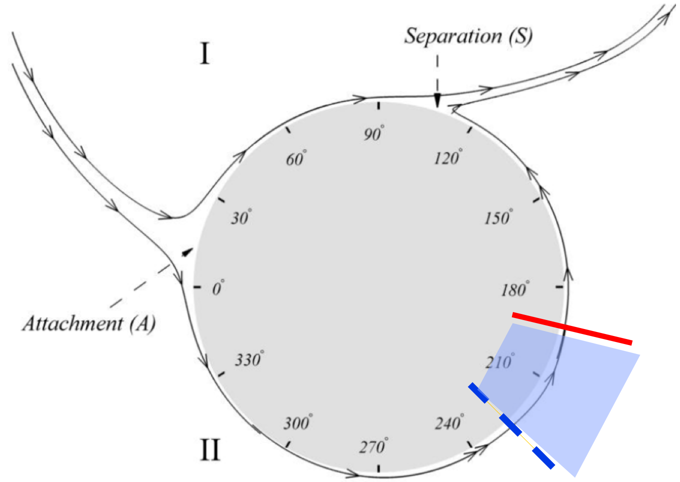


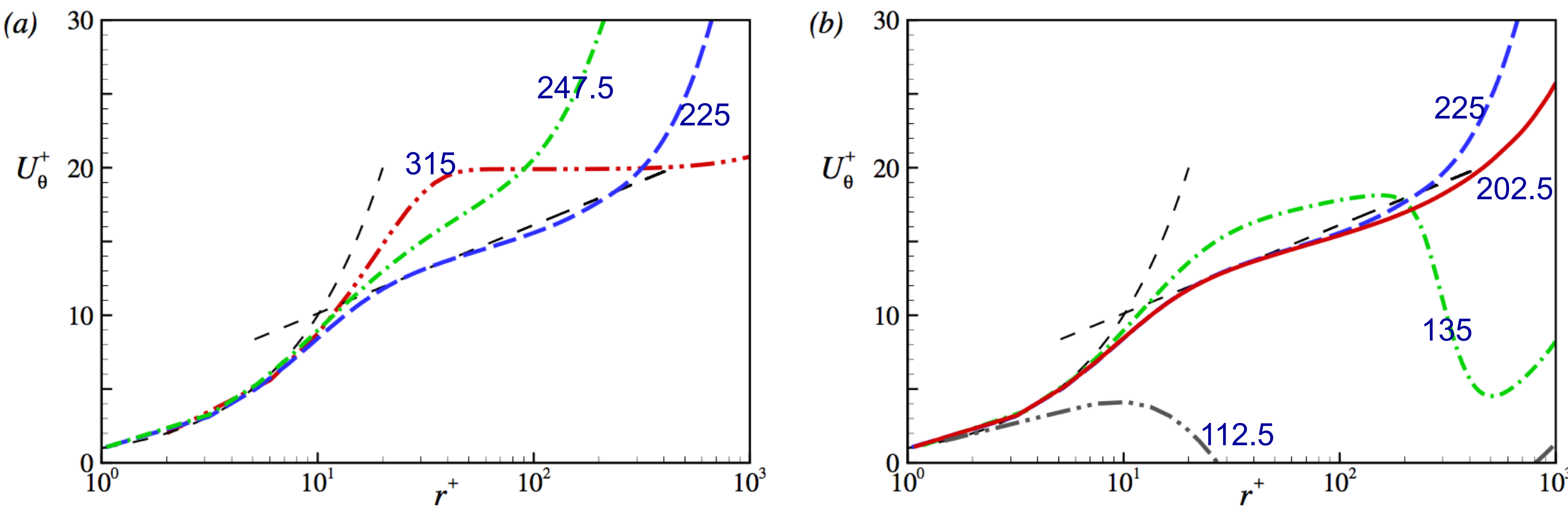


Discovery through simulation

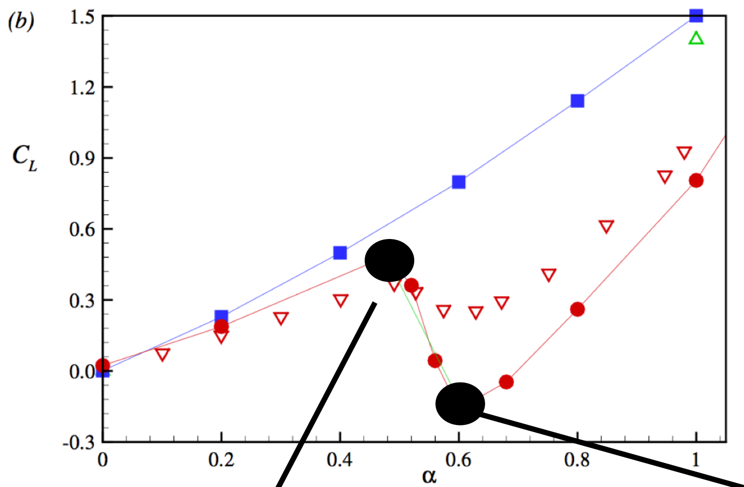
RC: turbulence observed at $\alpha=1.0$

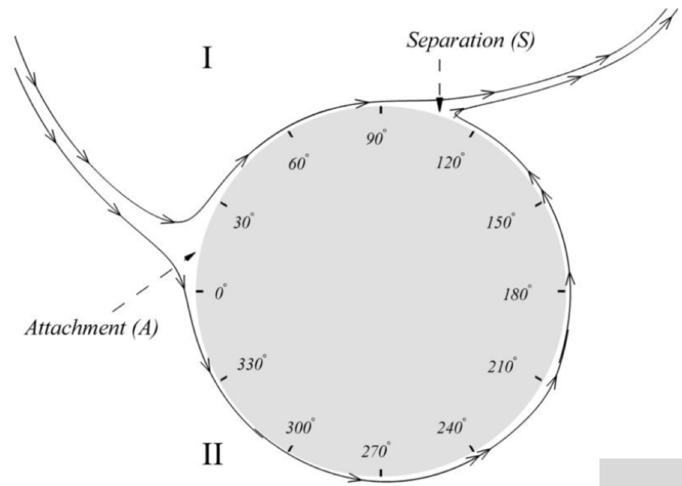




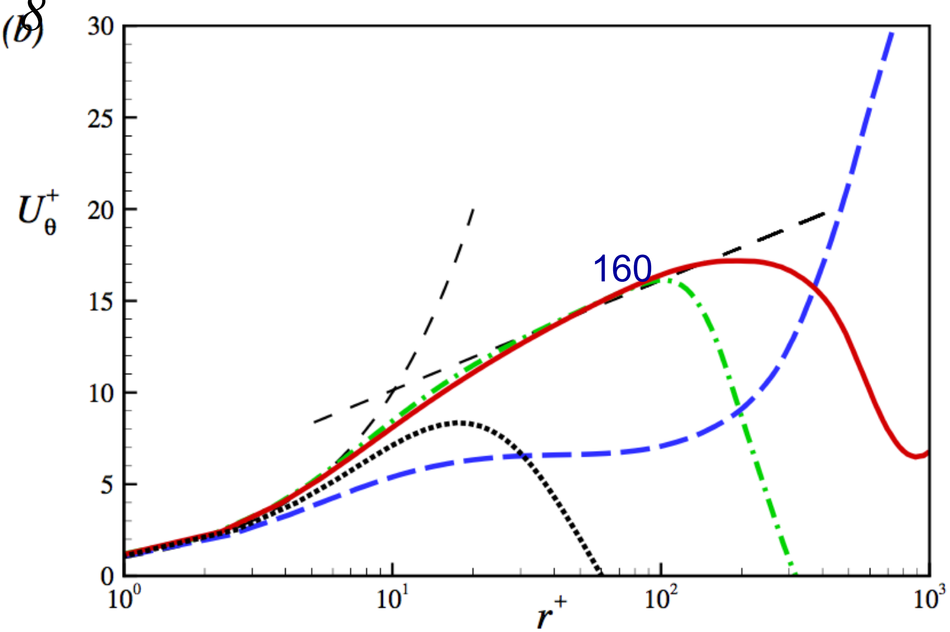


RC: No difference in turbulence across crisis

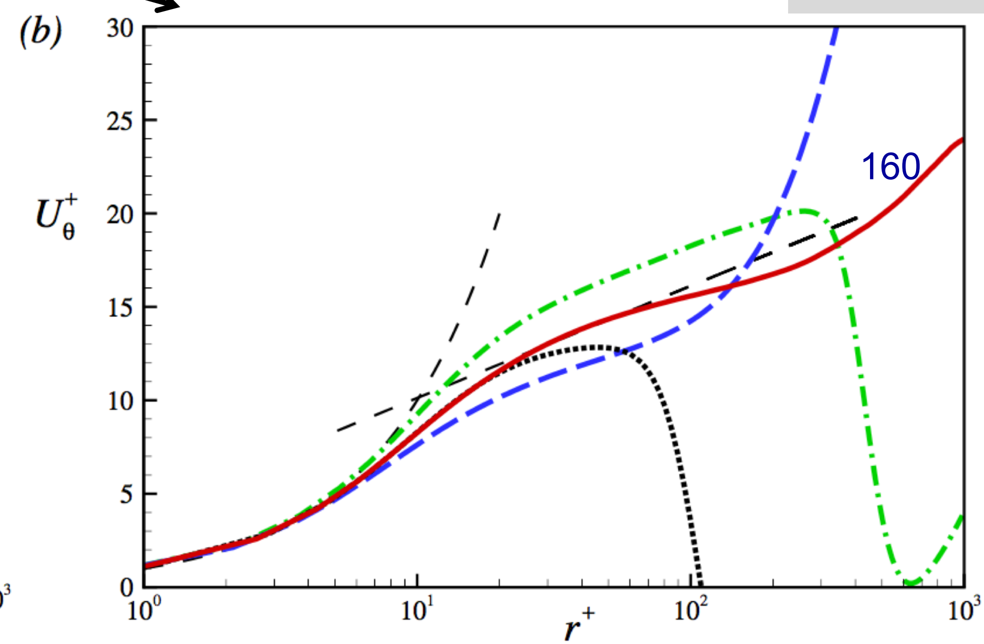




α=0.4
8



α=0.6



Cylinder + Grooved cylinder + Rotating cylinder

- Cylinder flow

Hypothesis: dynamic interaction between unsteady separations could be a more general mechanism for drag crisis in bluff body flow.

- Grooved cylinder
- Dynamic interaction between unsteady separations is still important.
- Mean flow: still observe the secondary separation bubble and prior separation bubble

- Rotating cylinder
- No primary separation on bottom.
- Unsteady separation dominates the flow.

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Discovery through simulation

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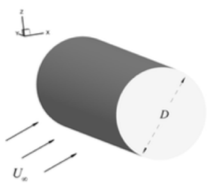
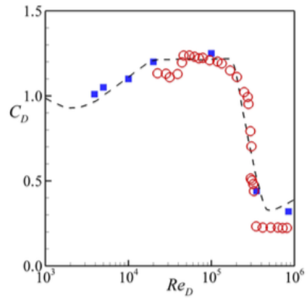
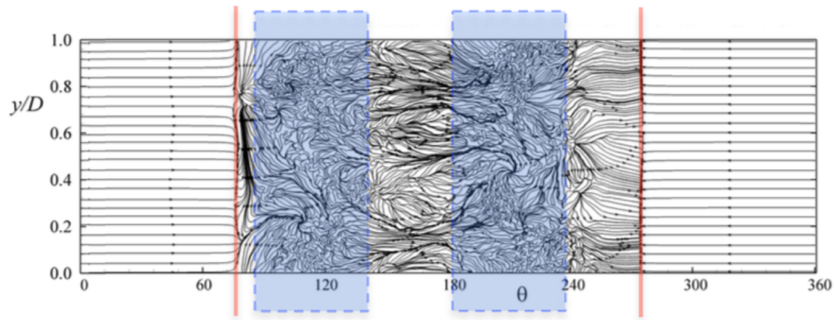
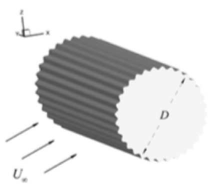
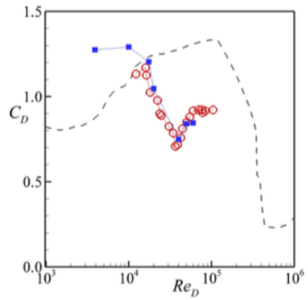
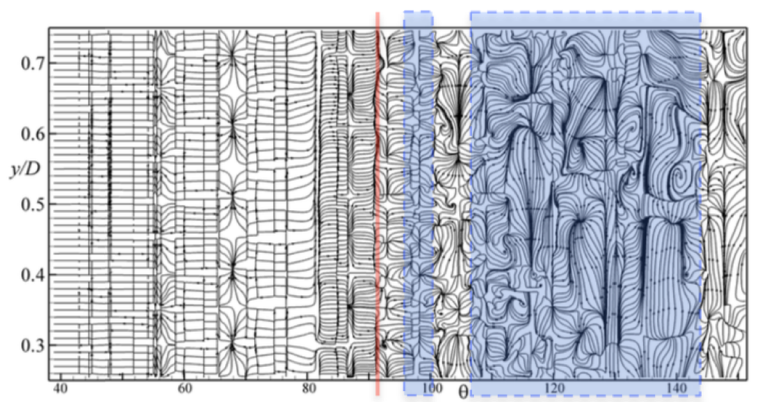
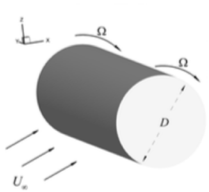
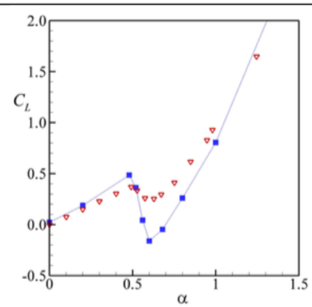
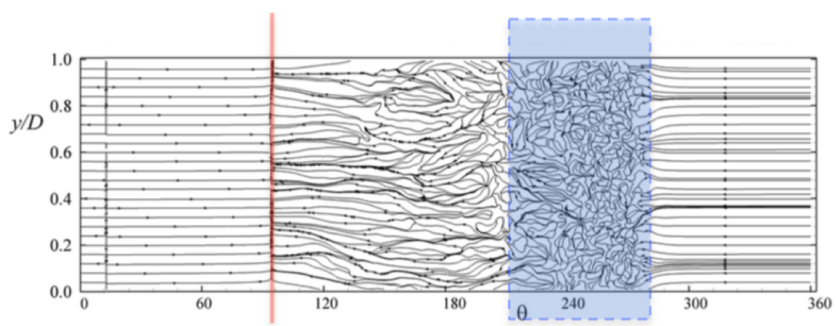
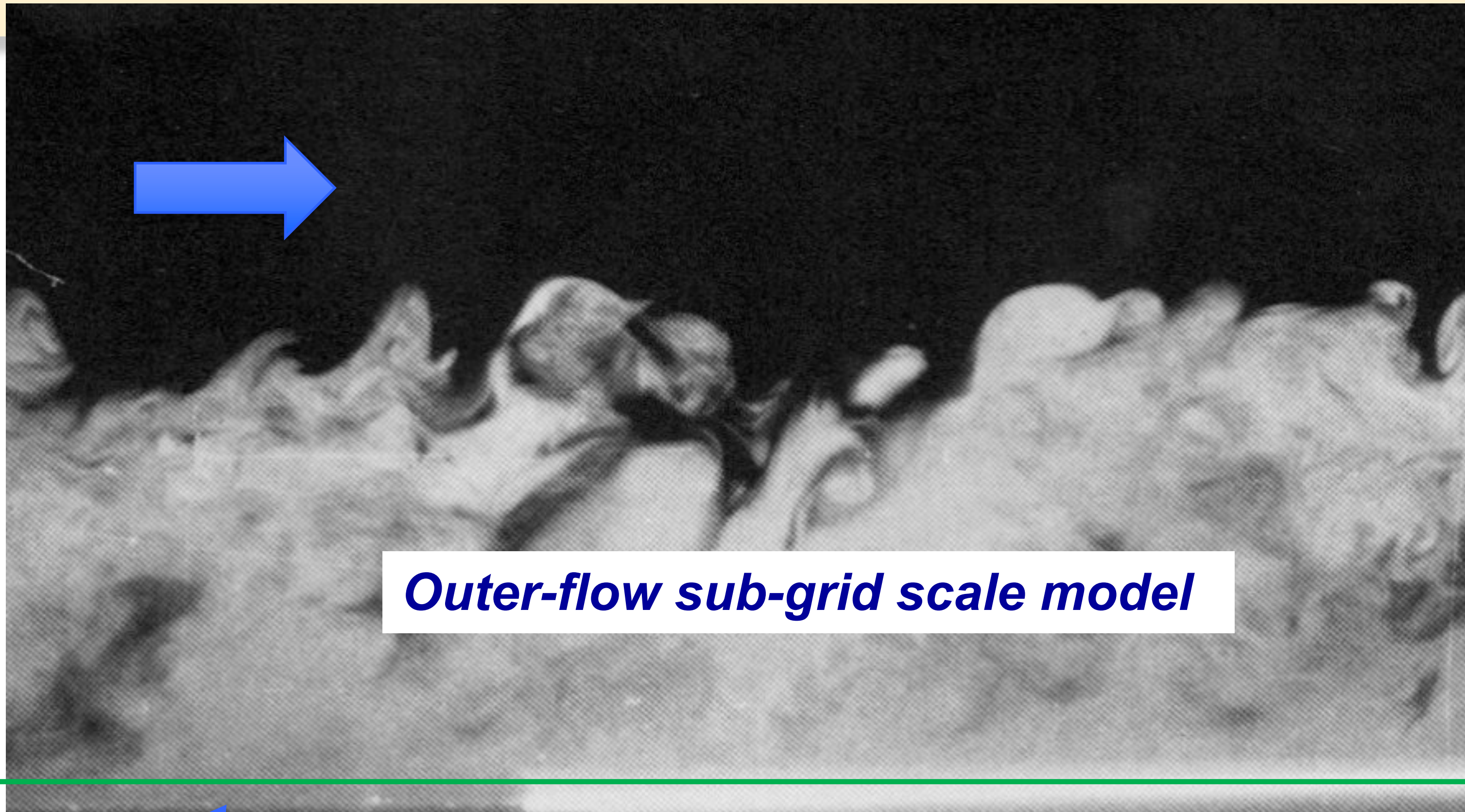
Geometric sketch	Drag/lift crisis (Symbols: hollow for experiments, filled for LES)	Instantaneous skin friction lines (red line for primary separation, blue zone for unsteady secondary separation)	Flow Mechanism	
			Interaction of separations	Turbulence effect
Smooth cylinder 			Yes	Yes
Grooved cylinder 			Yes	No
Rotating cylinder 			Yes	No

LES for wall-bounded flows



Wall-modeled region

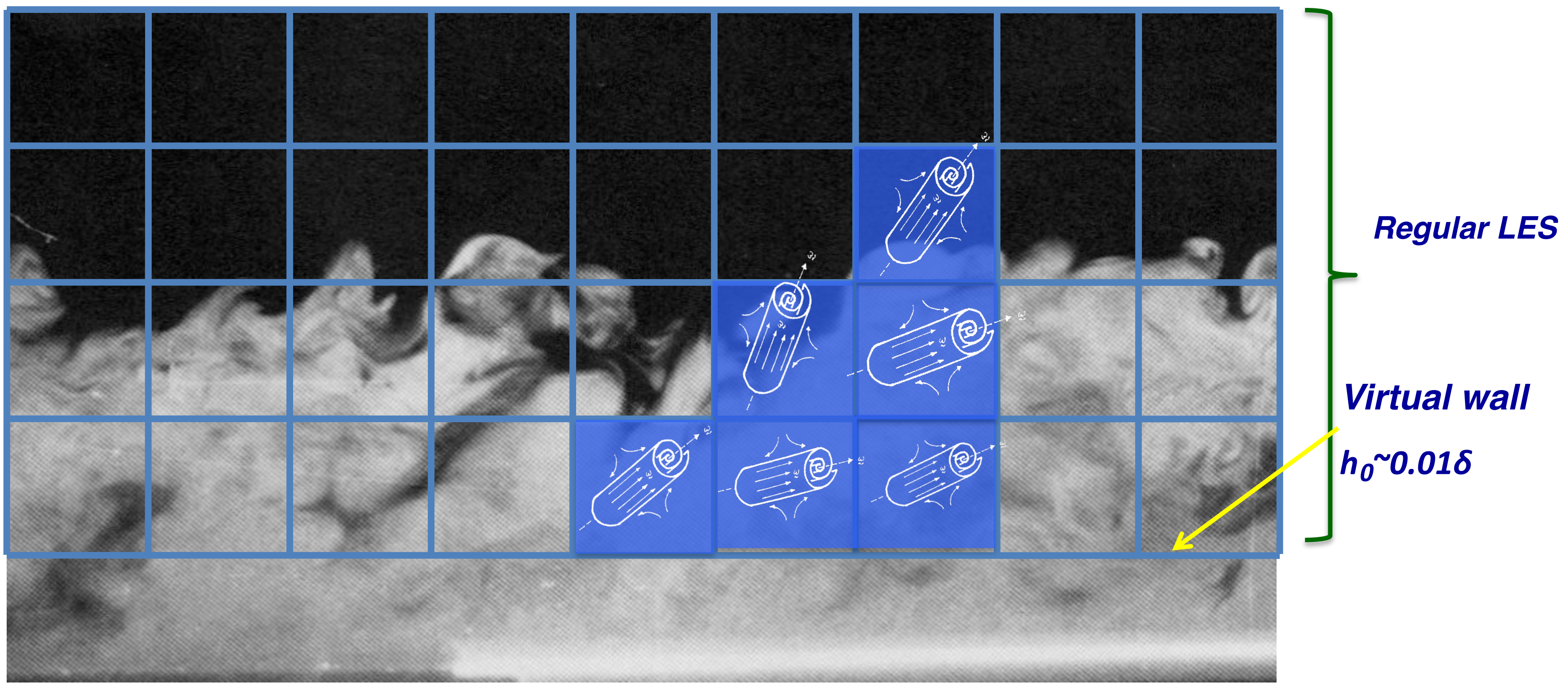
True wall

(Falco 1977)

Discovery through simulation

LES + wall model for high Re flow

Outer flow: LES with stretched-vortex SGS model



LES + wall model for high Re flow

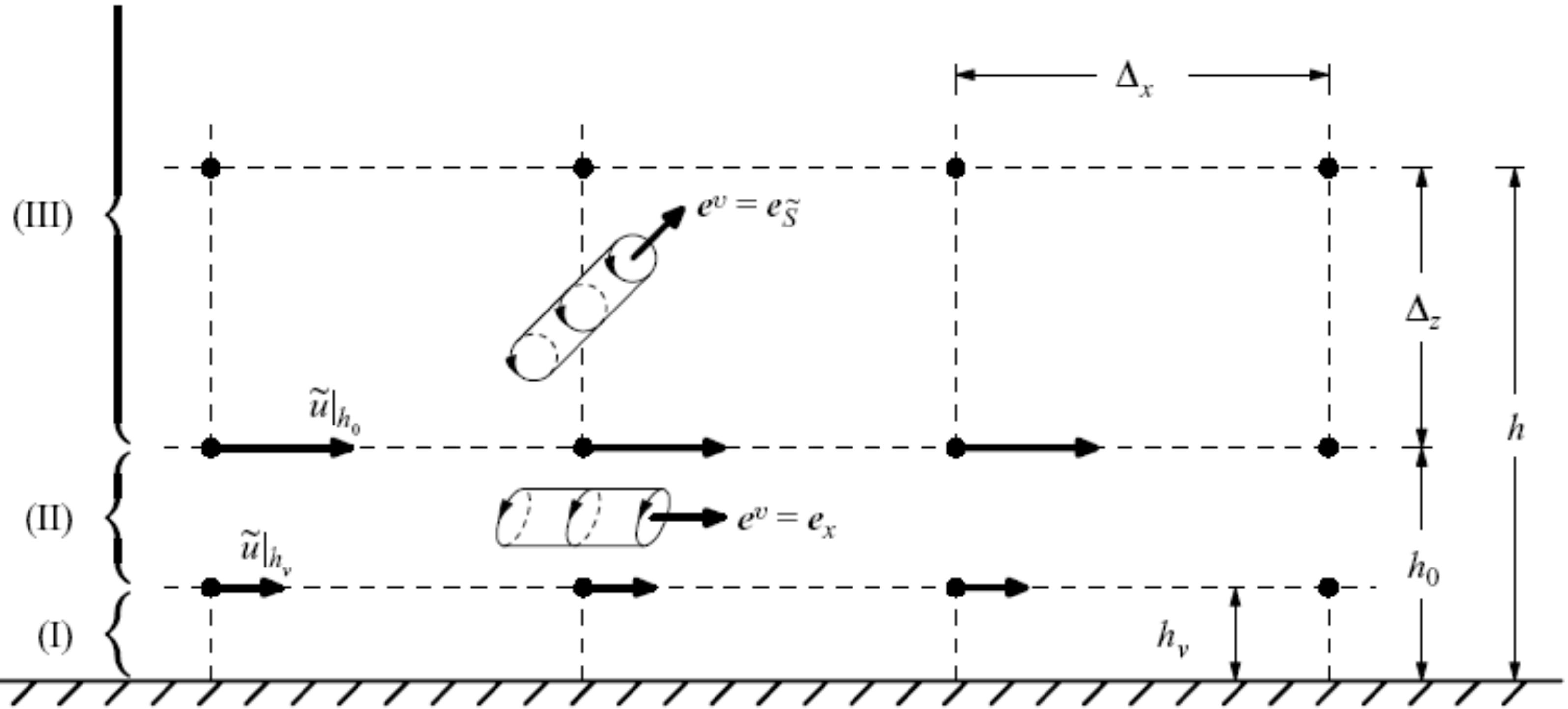


FIGURE 1. Schematic showing the near-wall set-up: h_0 locates the lifted virtual wall, where boundary conditions are applied; h locates the input plane to the wall shear stress equation, (3.10); h_v locates the outer edge of the viscous sublayer; $\boldsymbol{e}^v$ is the alignment of SGS vortices in their respective regions.

Discovery through simulation

Wall Model

Wall Model – Essential Idea

$$u, v, w, p \longrightarrow \tilde{u}, \tilde{v}, \tilde{w}, \tilde{p} \longrightarrow \langle u \rangle, \langle v \rangle, \langle w \rangle, \langle p \rangle$$

A general wall-parallel filter

wall-normal integration filter

- Inner scaling combined with wall normal integration filter

$$\frac{\tilde{q}}{u_\tau} = F(z^+), \quad z^+ \equiv \frac{z}{l^+} = \frac{z u_\tau}{\nu}. \quad \Longrightarrow \quad \frac{\partial \langle q \rangle}{\partial t} = \frac{\tilde{q}|_h}{2\eta_0} \frac{\partial \eta_0}{\partial t}.$$

- In the original model, applying the wall parallel filter

$$\frac{\partial \tilde{u}}{\partial t} + \frac{\partial \widetilde{uu}}{\partial x} + \frac{\partial \widetilde{uv}}{\partial y} + \frac{\partial \widetilde{uw}}{\partial z} = -\frac{\partial \tilde{p}}{\partial x} + \nu \frac{\partial^2 \tilde{u}}{\partial z^2},$$

- Main points to note
  - *Classical inner scaling*
  - *Near wall integration approach*

Discovery through simulation

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Wall Model

- ODE for wall shear stress (or u_τ) at every wall point $\quad u_\tau^2 \equiv \nu \eta_0 \quad \eta_0 \equiv \left.\frac{\partial \widetilde{u}}{\partial z}\right|_0$
  - Wall-normal integration of streamwise momentum equation
  - Top-hat filter normal to the wall, $0 < z < h$: $h = \Delta z > h_0$
  - Local inner-scaling reduction for unsteady term

$$\boxed{\frac{\partial \eta_0}{\partial t} = \frac{2\eta_0}{\widetilde{u}|_h}\left[-\frac{\partial \widetilde{uu}|_h}{\partial x} - \frac{\partial \widetilde{uv}|_h}{\partial y} - \frac{\partial \widetilde{uv}|_h}{\partial y} - \left.\frac{\partial \widetilde{p}}{\partial x}\right|_h + \frac{\nu}{h}\left(\left.\frac{\partial \widetilde{u}}{\partial z}\right|_h - \eta_0\right)\right]}$$

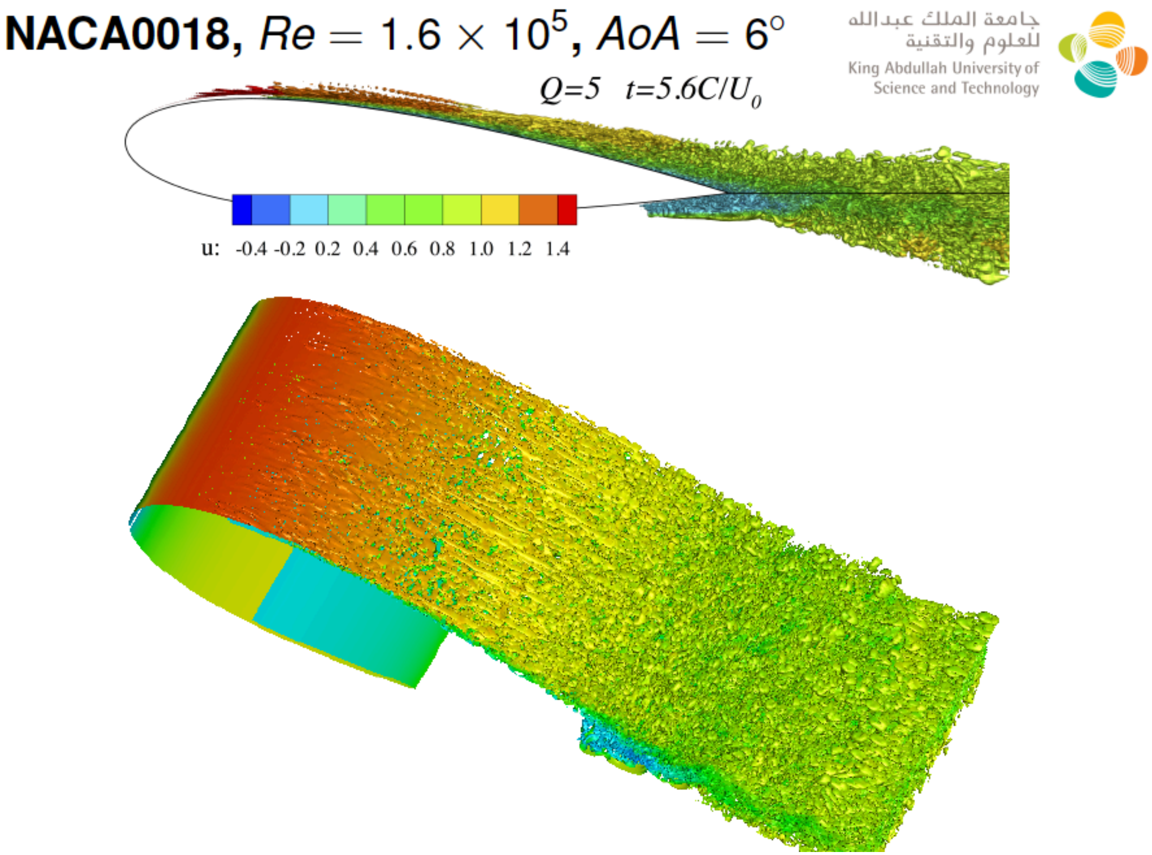
- Attached-eddy ansatz in overlap region (Townsend, 1976)
  - Hierarchy of streamwise ``attached'' SGS vortices whose size scales with distance from wall
  - Extended stretched-vortex SGS model with attached-eddy assumption
  - SGS model gives log relationship for slip-velocity at lifted wall position $z = h_0$
  - ``Karman constant'' calculated dynamically

$$\boxed{\widetilde{u}|_{h_0} = u_\tau \left(\frac{1}{\mathcal{K}_1}\log\left(\frac{h_0 u_\tau/\nu}{h_\nu^+}\right) + h_\nu^+\right)} \qquad \mathcal{K}_1 = \frac{\gamma_{II} K^{1/2}}{2\left(-\left.T_{xz}\right|_{e_{\widetilde{S}}}\right)^{1/2}}$$

Wall Model Development & Applications in LES

- LES of flat plate TBL: power law vs. log law
  - *Cheng & Samtaney, Phys. Fluids 2014*
- LES of separation/reattachment of flat plate TBL
  - *Cheng, Pullin, Samtaney: JFM 2015*
- LES of flow past an airfoil
  - *Gao, Cheng, Zhang, Samtaney (JFM under review)*

Flow past Airfoils



Discovery through simulation

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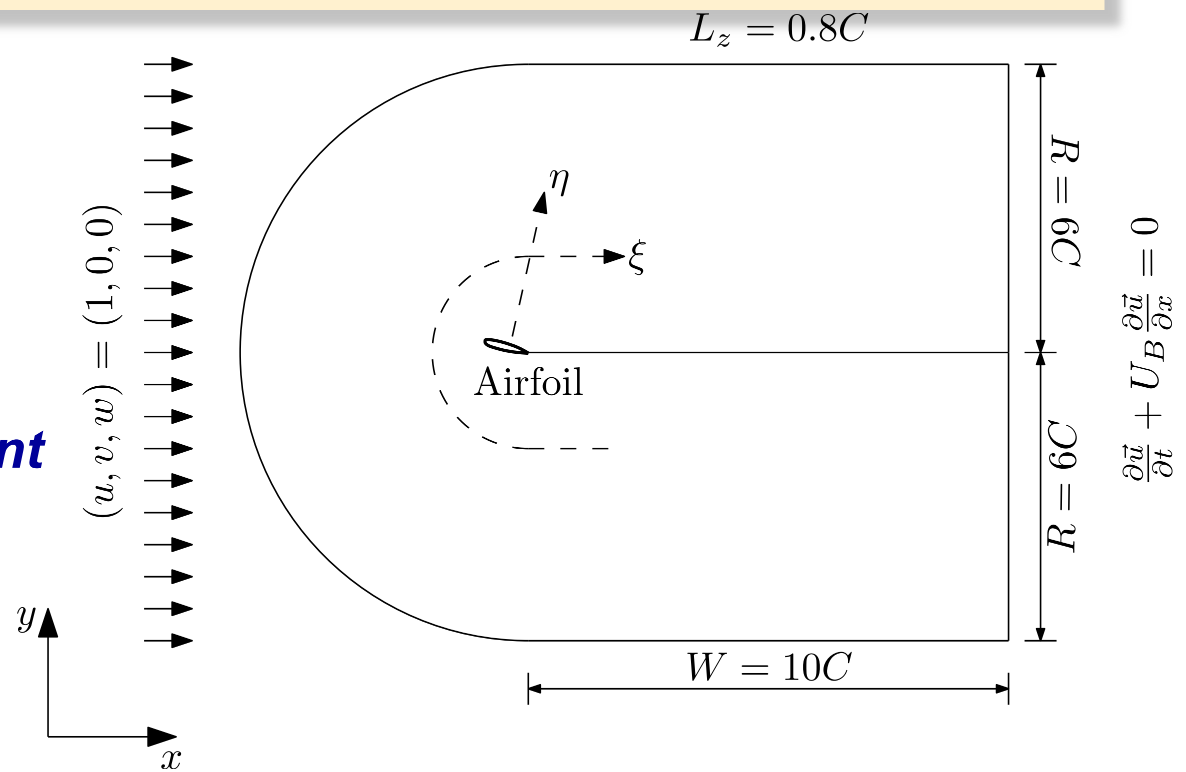
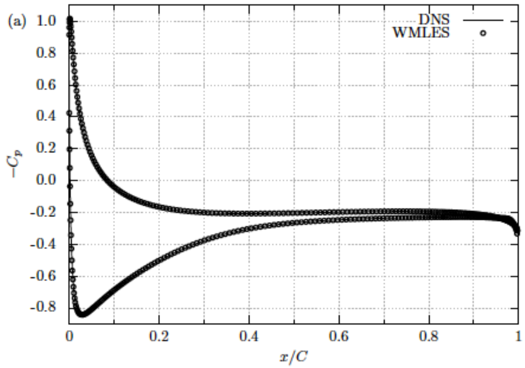
Numerical Setup

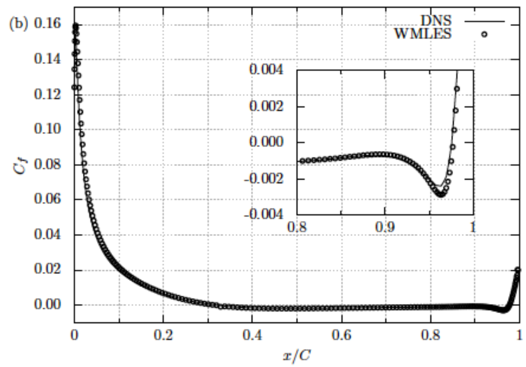
- ***Comparison between DNS and WMLES at Re=10⁴***
- ***Comparison between WMLES and experiment at Re=10⁵, 2.1 x 10⁶***



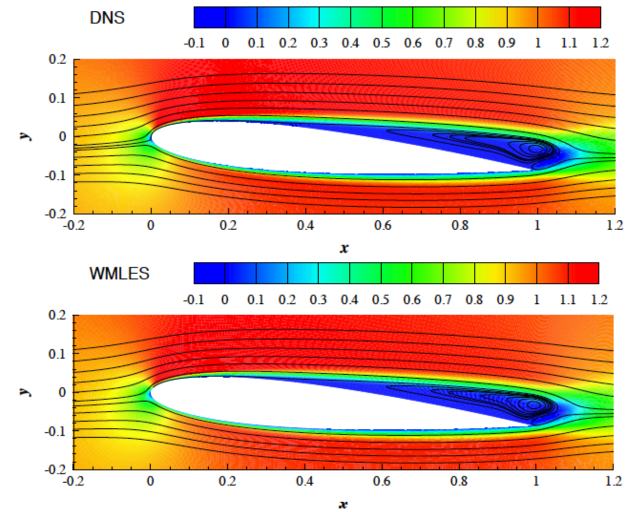
Airfoil	Method	Re_c	AoA	$N_\xi \times N_\eta \times N_z$	$\Delta\xi^+_{max}$	$\Delta\eta^+_{max}$	Δz^+_{max}
NACA0012	DNS	10^4	5°	$2048 \times 256 \times 256$	7.4	0.8	8.8
NACA0012	WMLES	10^4	5°	$768 \times 96 \times 64$	19.7	14.2	38.4
NACA0018	WMLES	10^5	5°	$1600 \times 128 \times 128$	54.9	15.8	65.8
A-Airfoil	WMLES	2.1×10^6	13.3°	$3200 \times 256 \times 256$	80.1	16.4	85.4

NACA0012, Re=10^4, AOA=5

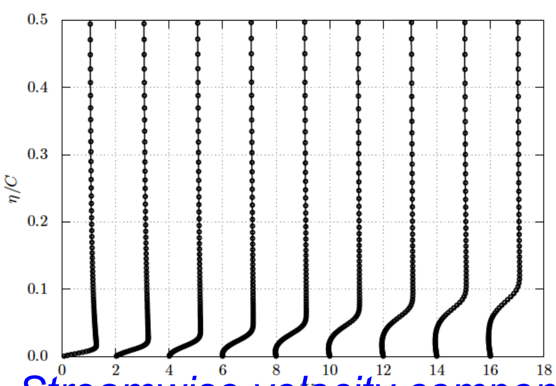




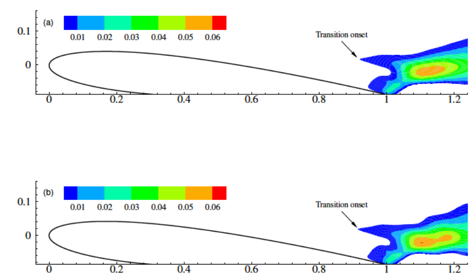
Time and spanwise averaged pressure coefficient and skin friction coefficient



Time and spanwise averaged streamwise velocity component and streamlines



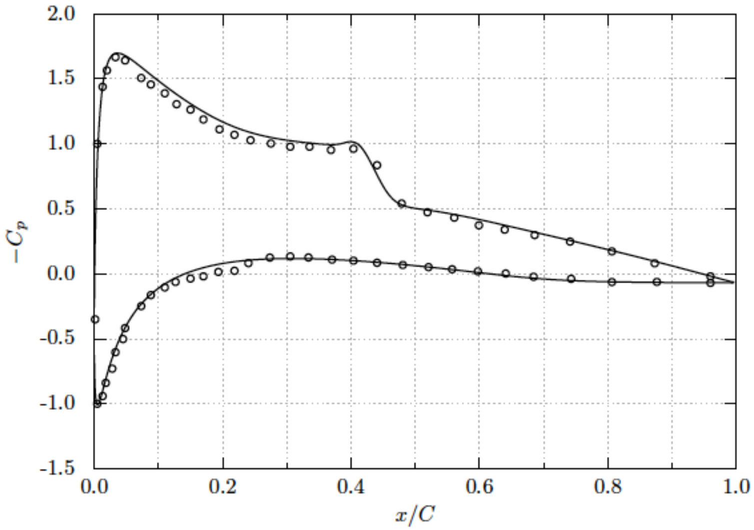
Streamwise velocity component on suction side from x=0.1 to 0.9.

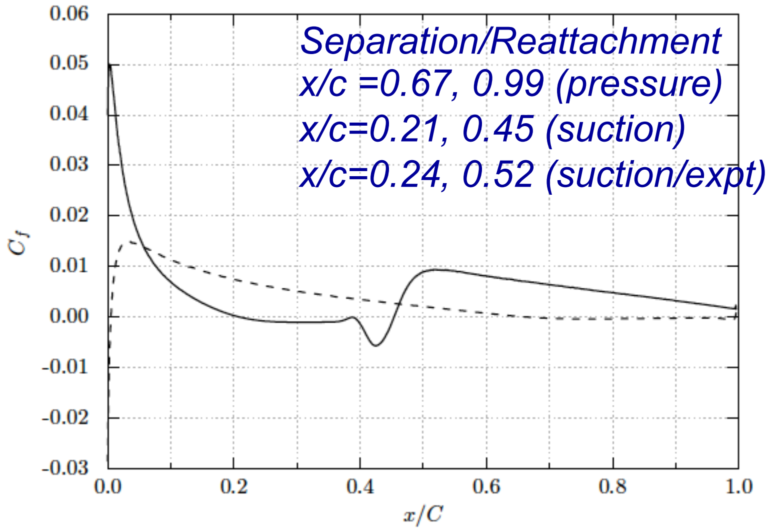


- Contour plot of Reynolds stress ($-\overline{u'v'}$), transition criterion: $-\overline{u'v'} = 0.001$.

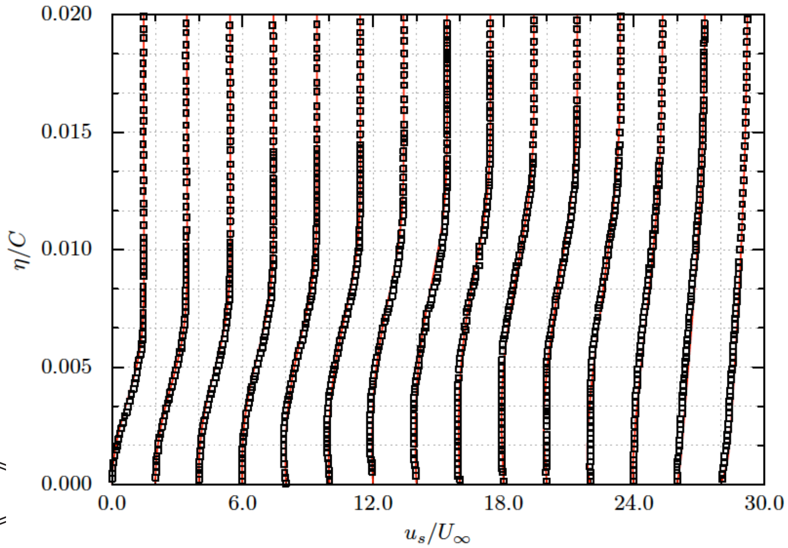
Discovery through simulation

NACA0018, Re=10^5, AOA=5

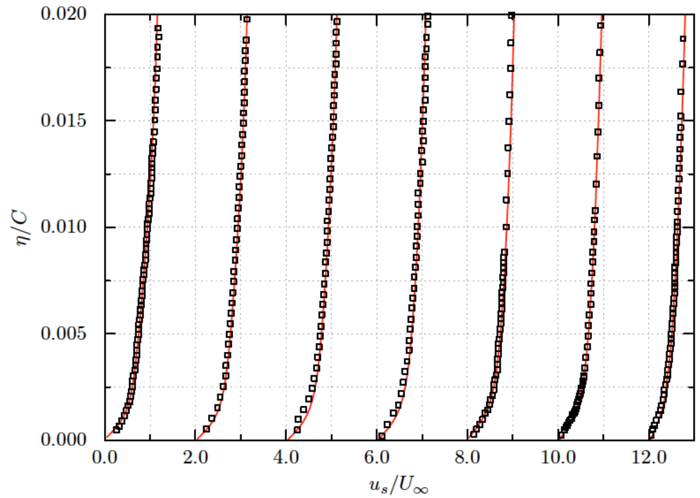




Symbols: Expts of Kirk & Yarusevych (2017)

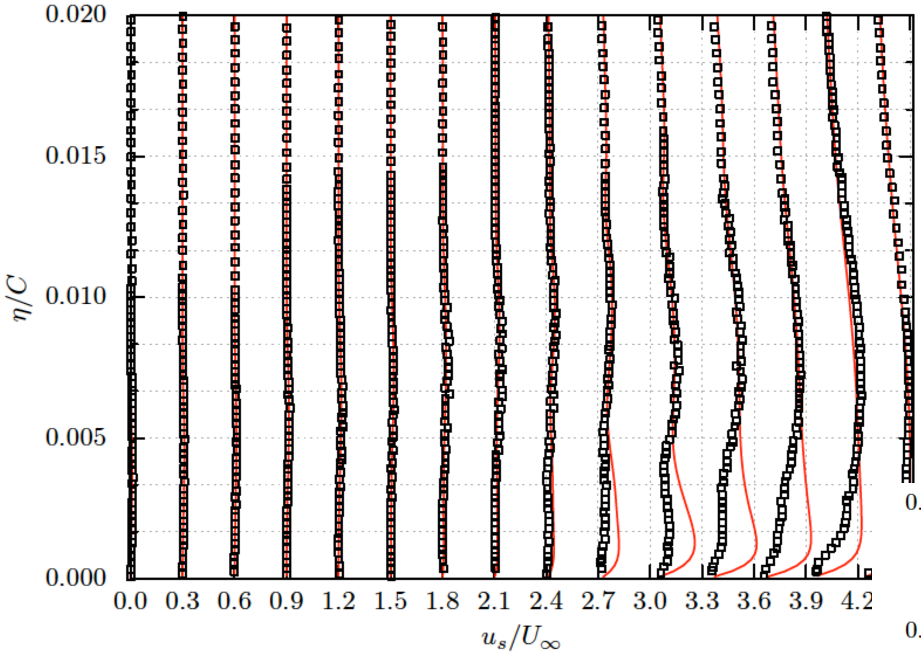


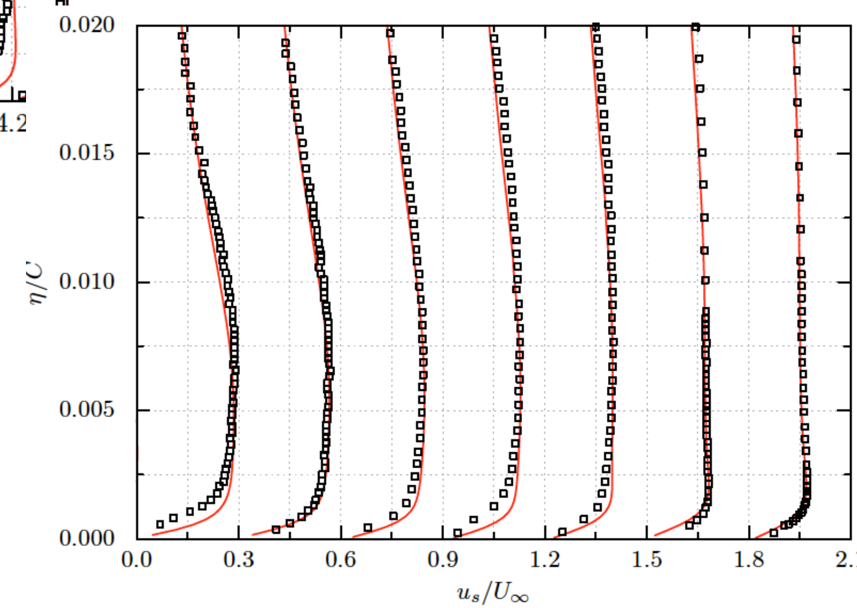
Mean velocity profiles x/c=0.2-0.5



Mean velocity profiles x/c=0.52, 0.54, 0.6, 0.66, 0.73, 0.87

NACA0018, Re=10^5, AOA=5

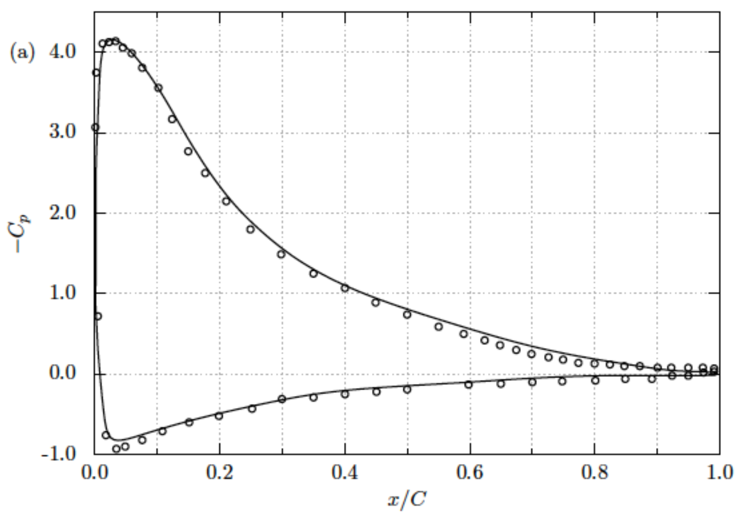


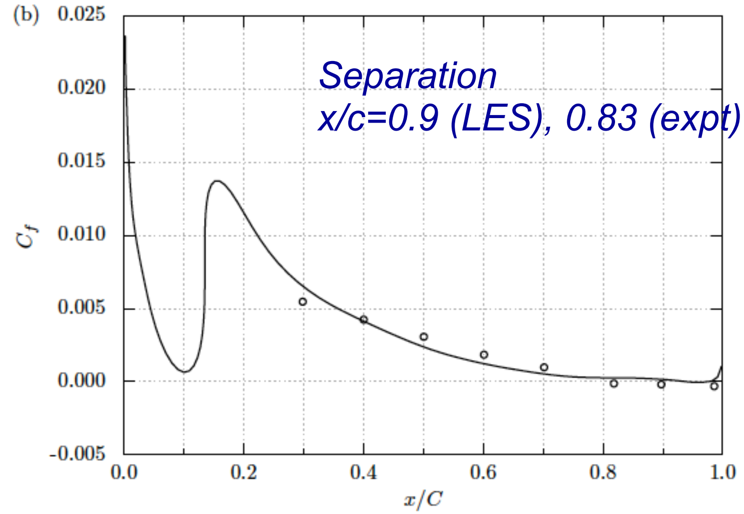


Discovery through simulation

Mean velocity profiles

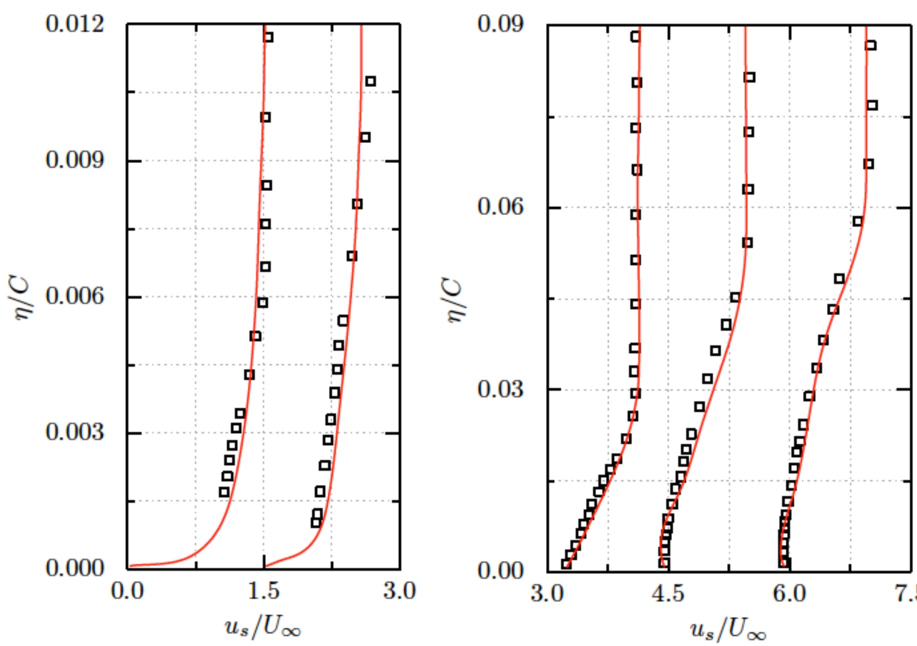
A-airfoil, Re=2.1x10^6, AOA=13.3





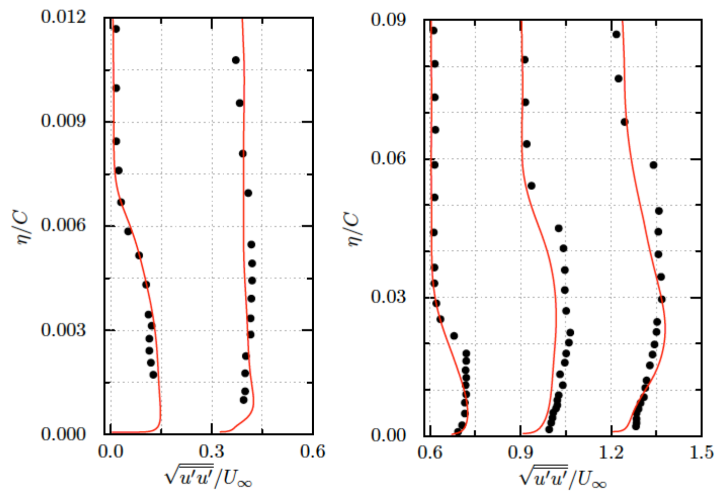
Symbols: Expts of Mary & Sagaut (2002)

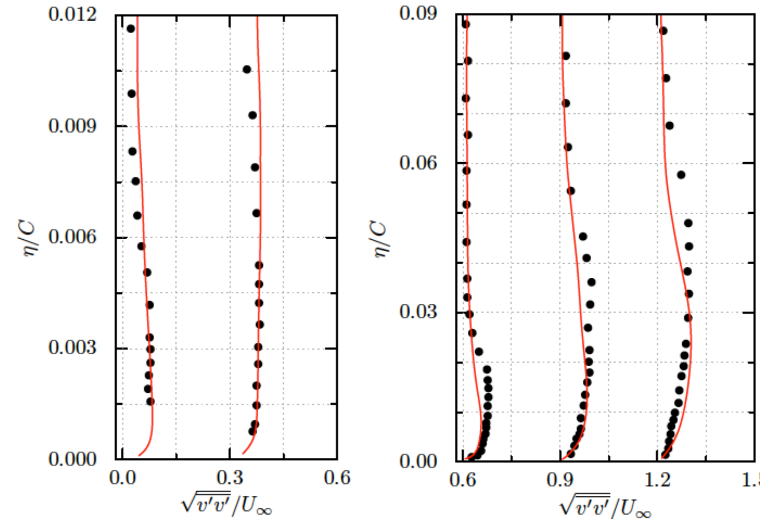
Mean velocity profiles



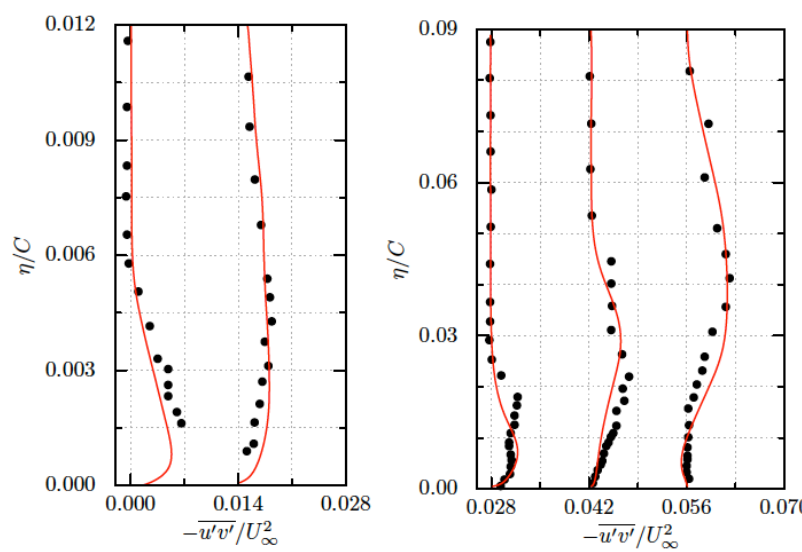
Discovery through simulation

A-airfoil, Re=2.1x10^6, AOA=13.3





Reynolds stress



Discovery through simulation

Conclusion

Is unsteady separation important in other canonical flows?

- Cylinder flow:
  - Interactions between unsteady separations, turbulence transition
- Grooved cylinder flow
  - Interaction between unsteady separations, no turbulence transition on surface
- Rotating cylinder flow
  - One unsteady separation, no turbulence transition on surface
- Unsteady separation is a dominant mechanism in cylinder-type flows.
- Drag crisis observed for SC, GC, RC: turbulent transition plays a role only in SC

Progress in flows past airfoils

- Preliminary results indicate WMLES can handle separation effectively

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Thank you

- Acknowledgement

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Smooth cylinder	Grooved cylinder	Rotating cylinder
40M	35M	30M

- Questions?

fps
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